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Technical Report

Model Test Report of a 100,000 Ton Heavy Lift Ship as a Seabased Intermediate Transfer Station

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14. ABSTRACT
This report describes the second phase of sub-scale testing undertaken at for the CISD developed Intermediate Transfer Station (ITS). Phase I testing used a 50,000 ton Heavy Lift Ship (HLS) and concentrated on a med-moor configuration. Phase II introduced a wider range of configurations, including skin-to-skin, bow-to-stern, and varied headings with the use of a HLS approximately twice the size of the small HLS. The main objectives of the Phase II testing were to quantify the lee produced by the different configurations, determine the likelihood of deck wash and ramp torsion, compare and contrast varying ITS configurations, and to observe the relative ship motions.
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Abstract

This report describes the second phase of sub-scale testing undertaken for the CISD developed Intermediate Transfer Station (ITS). Phase I testing used a small Heavy Lift Ship (HLS), the MV Tai An Kou, and concentrated on a med-moor configuration. Phase II introduced a wider range of configurations, including skin-to-skin, bow-to-stern, and varied headings, with the use of a larger HLS, the MV Blue Marlin, which is approximately twice the size of the Tai An Kou.

The ITS concept uses a Ro/Ro vessel med-moored to a HLS within a seabasing environment. The large, clear deck of the HLS can be used to transfer wheeled and tracked vehicles, personnel and material from the Ro/Ro ship or other large ships on to lighters such as Landing Craft Utility (LCU) and Landing Craft Air Cushion (LCAC) vessels. Today, the Roll on Roll off Discharge Facility (RRDF) acts as the transfer station. Operations with the RRDF are limited to Sea State 2 due to relative motions, personnel safety and ramp torsion.

Arranging the Ro/Ro ship and HLS in a med-moor configuration with the Ro/Ro aligned head to the dominant sea direction, roll and pitch motions are decoupled since the primary response of the Ro/Ro is pitch and the primary response of the HLS is roll. Torsional loading on the Ro/Ro stern ramp is thereby minimized. Positioning the Ro/Ro vessel alongside the HLS in a skin-to-skin configuration utilizes the side port ramp of the Ro/Ro as the means of transfer. The torsional load experienced on the ramp is dependant upon the relative motions of the two ships.

In the med-moor configuration, listing the 100,000 ton HLS by 2° creates a 'high-side' and 'low-side'. The high-side reduces the drop down angle of the stern ramp on the Ro/Ro ship and acts as a seawall. The low-side of the HLS provides a simple interface

for the lighters. LCACs fly on to the deck to load and unload (which requires going off-cushion) and LCUs drop their bow ramp onto the deck of the HLS.

The main objective of the Phase II ITS testing was to quantify the lee produced in varying configurations in order to assess potential improvements to lighter operations. Secondary objectives were to determine the likelihood of deck wash and ramp torsion and the corresponding conditions most likely to cause them, to compare and contrast varying ITS configurations, and to observe the relative ship motions throughout.

There were four models used during testing, each at a scale of 1:158, representing a Large Medium Speed Ro/Ro (LMSR), two HLSs, and a LCU 2000. The configurations were tested by having two sonic wave probes placed upstream of the configuration to record the incident wave height, and nine wave probes located in the lee. There were four main configurations tested, each compared with regard to size of the lee created, torsional effect on the ramp, throughput capability, relative motions between vessels, and deck wash observed.

The principal conclusion from testing is that the med-moor and the skin-to-skin in beam seas configurations produced the greatest reduction in wave height in the lee over the largest area. The choice between med-moor or skin-to-skin will depend on other considerations such as throughput, safety, and ramp torsion which are also dependent on the type of mooring configuration. Further study is needed in these areas to determine which of these two configurations is most suitable as an Intermediate Transfer Station.

Acknowledgements

This project would not have developed as it did without the assistance of numerous people at NSWCCD, mainly from within Code 50 and the model shop. In particular, Dr. Colen Kennell and Mr. Mark Selfridge (UK MoD Exchange Officer) are noted for providing invaluable insight and advice in marine engineering and naval architecture throughout the project. Our thanks is also extended to Mr. Matthew Powell who provided a number of components and assisted in the data acquisition process, and also to Mr. John Hamilton for assisting with and implementing the wavemaker. Thanks is further extended to the UK MOD for their continuing foresight in the value of having graduates undertake placements with NSWC - Carderock.

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INTRODUCTION

Seabasing

The recent conflicts in Iraq and Afghanistan have highlighted the dependence of our military on other nations to conduct large-scale operations sizeable distances from the Continental United States (CONUS). We relied heavily on third party host nations to provide air bases, ports, command and control centres, and other facilities in conducting offensive operations, and suffered a loss in capability when Turkey (NATO member) refused to allow any significant level of access to coalition forces during Operation 'Iraqi Freedom'. This highlights that, especially since the response to the terrorist attacks of 11th September 2001, political and religious considerations now often outweigh military ties.

To counter this reliance on third party host countries the idea of a Sea Base has been developed. It incorporates moving away from large-scale amphibious assaults and moving towards light, rapidly deployable, highly maneuverable forces capable of beaching on to the coast and transporting inland to their objective. The Sea Base would be responsible for providing both a staging area and logistical support to the troops.

Some early concepts of seabasing focused on large mobile offshore bases that could be capable of accommodating airlifter-sized aircraft such as the C-130J. These have been expanded to include facilities for accepting, sorting and forwarding personnel and materiel along with the capability to retrieve both personnel and material and provide medical facilities. The Sea Base concept has since moved further towards a collection of dispersed vessels that can provide individual capabilities such as those mentioned above as well as defense assets such as Command & Control, Communications, Computers and Intelligence (C4I) nodes and Intelligence Surveillance Reconnaissance (ISR) network nodes in the combination desired for any particular mission.

Abreviations

C4I	–	Command and Control, Communications, Computers and Intelligence
CISD	–	Center for Innovation in Ship Design
CONUS	–	Continental United States
CSG	–	Carrier Strike Group
EFV	–	Expeditionary Fighting Vehicles
ESG	–	Expeditionary Strike Group
HLS	–	Heavy Lift Ship
ISR	–	Intelligence Surveillance Reconnaissance
ITS	–	Intermediate Transfer Station
LCU	–	Landing Craft Utility
LMSR	–	Large Medium Speed Ro/Ro
MPG	–	Maritime Positioning Group
NATO	–	North Atlantic Treaty Organization
RRDF	–	Roll on Roll off Discharge Facility

A future Sea Base may be positioned at least 25nm from shore, from which LCACs and Expeditionary Fighting Vehicles (EFVs) can reach the beach in under an hour. Distances up to 250nm have been stated (the range of MV22). If the situation allows, the Sea Base may be able to move closer to shore to allow the slower LCU landing craft, which can transport heavier equipment, to be offloaded in a reasonable length of time as well as being close enough to pump water and fuel from the Sea Base across the beach.

ITS Description

The ITS concept utilizes a HLS to transfer troops and equipment from a Ro/Ro ship onto individual transports such as the LCU 2000 and the LCAC. These can then be used to transport the equipment from the Sea Base to the landing area.

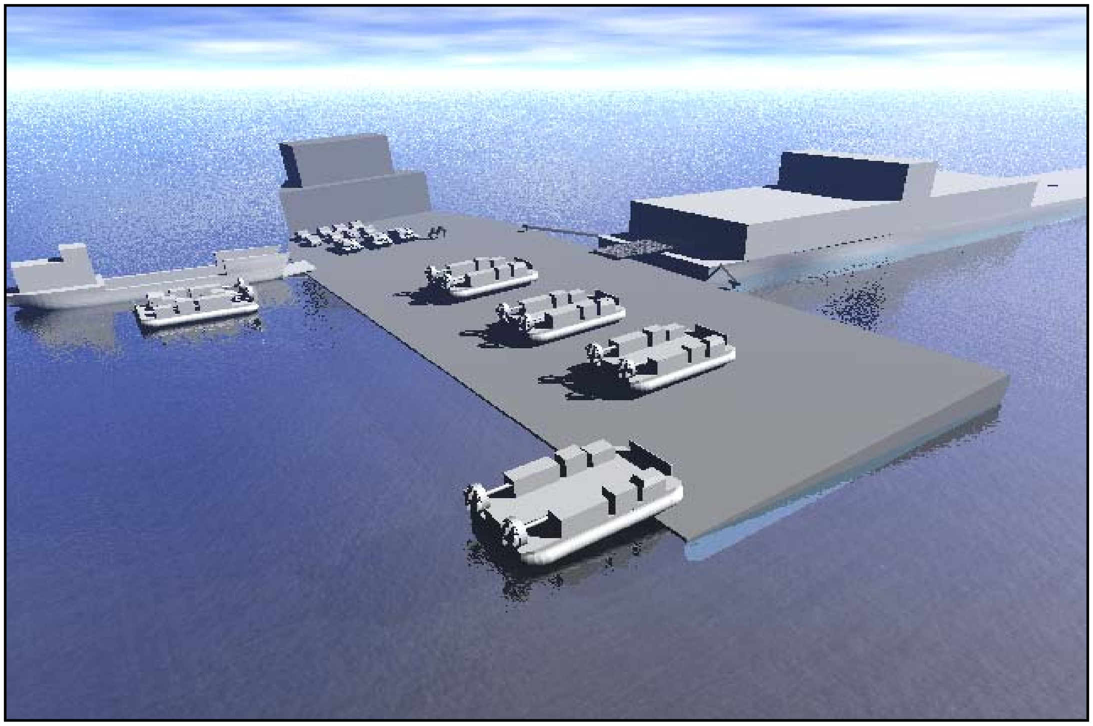


Figure 1 - Med-Moor Arrangement

As seen in Figure 1, the equipment is transferred from the Ro/Ro Ship to the HLS using the stern ramp. Equipment such as wheeled and tracked vehicles, along with supplies can then be loaded onto the LCAC whilst it is on the deck of the HLS, or by simply driving up the ramp of an LCU.

At present, in-stream cargo operations are limited to sea state 2 and below. It is intended that the Ro/Ro ship will be pointed into the prevailing seas with the HLS heeled slightly to provide a lee on the loading side of the ship. The objective in creating this lee is to enable operations to take place in heavier seas than sea state 2. The heeling of the ship will also allow for LCACs to fly onto the HLS and come off cushion, and will provide easier access for the LCUs to interface with the HLS.

PHASE II OBJECTIVES

The objectives of the ITS Phase II testing were to:

1. quantify the lee (Wave height and extent/variation) in different configurations.
2. observe any deck wash on HLS and identify causing conditions.
3. observe any torsion on the ramp and identify causing conditions.
4. observe relative ship motions.
5. compare and contrast different mooring configurations.

MODEL CONSTRUCTION

A 1:158 scale model of the Tai An Kou HLS and LMSR Ro/Ro Vessel were available for use from previous model testing. A major goal of Phase II testing was to analyze the effectiveness of using a larger HLS. In addition to the models used in Phase I, a 1:158 scale model of the MV Blue Marlin was manufactured.

3D Model

The hull lines for the Dockwise owned and operated MV Blue Marlin were made available, and the data was used to construct a 3D model. It was decided for simplistic purposes that the superstructure would be added at a later stage as a separate section.

Model Manufacture

The 3D model of the hull was used by the workshop at NSWC Carderock Division to produce a cutting pattern, from which the CNC machine formed the shape of the hull out of Renwood. The interior of the hull was hollowed out to provide a hull thickness of 1 inch.

The deck of the HLS was made from a piece of Plexiglas with a series of screws placed around its perimeter for it to be fixed to the hull. This also allowed the flexibility of removing and replacing the deck when required. To ensure a watertight seal between the deck and the hull a gasket was placed between the two. The superstructure of the model was made out of foam, and simply attached to the deck once the model was completed.

Ballasting

Ballast weights were added inside the hull of the model to ensure that the correct draught and center of gravity were achieved. This was accomplished by carrying out an inclining experiment on the model. The details of this experiment can be seen in Appendix D.

TESTING CONFIGURATIONS

The testing configurations investigated in Phase II involved both med-moor configurations and skin-to-skin configurations with varying heading and varying separation between the vessels. The following diagrams illustrate what configurations were tested and how each configuration was structured.

ITS Blue Marlin – Med-Moor Configuration

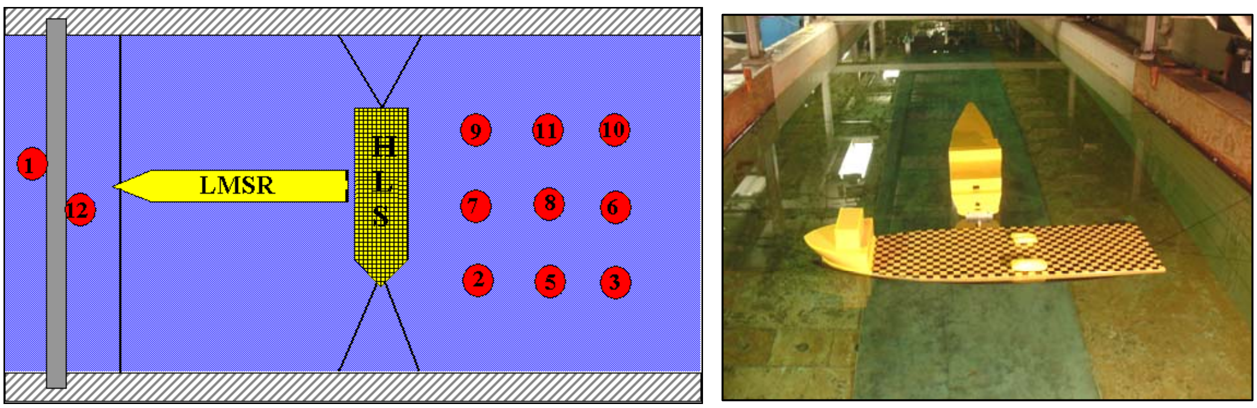


Figure 2 - Med-Moor Configuration

The med-moor configuration is the same as that used in Phase I testing, but using a larger HLS, modeled on the MV Blue Marlin. The configuration is formed by having the Ro/Ro vessel head on to the incident waves, and moored perpendicular to the HLS so that the HLS is at beam seas to the incident waves.

The Ro/Ro was moored to both sides of the tank using bungee lines attached to either side of the bow of the model, level with the surface of the water, and located where the bow thrusters would be on the full-scale ship. The HLS ship was moored to both sides of the tank by having two bungee lines at the bow and two bungee lines at the stern. Finally, to moor the two vessels together a pin-joint was used that would allow the two to be attached but left both models with the ability to move freely. The exact mooring dimensions and locations of the models can be seen in Figure 3.

Throughout the med-moor testing the HLS ship was heeled to an angle of 2.0° to provide a freeboard on the windward side of 2.0m, and to allow for the lee side of the deck edge to be level with the water. As previously mentioned this is to facilitate the LCACs transition from the water on to the deck of the HLS.

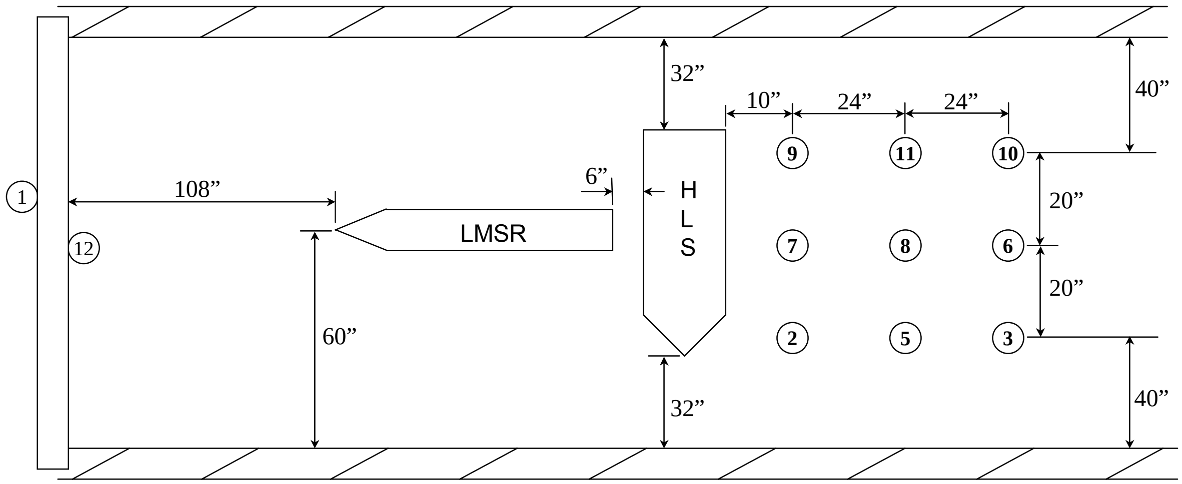
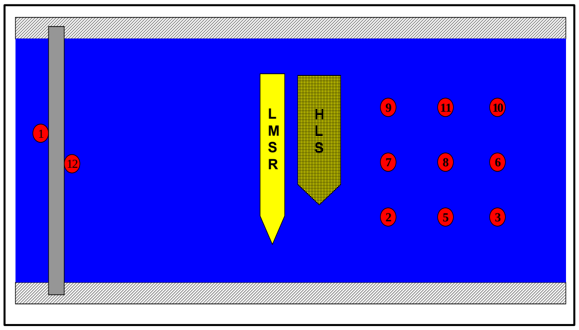


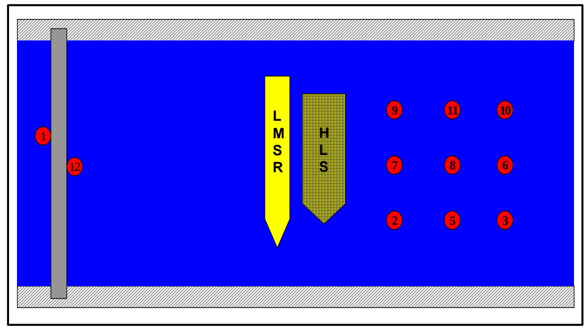
Figure 3 - Med-Moor Testing Details

Skin-to-Skin Configuration – Beam Seas

The skin-to-skin in beam seas configuration, Figure 4, was of particular interest as it was envisaged that having the larger Ro/Ro Vessel placed between the incident waves and the HLS would produce a larger lee. This allows the use of the Ro/Ro's side ramp.

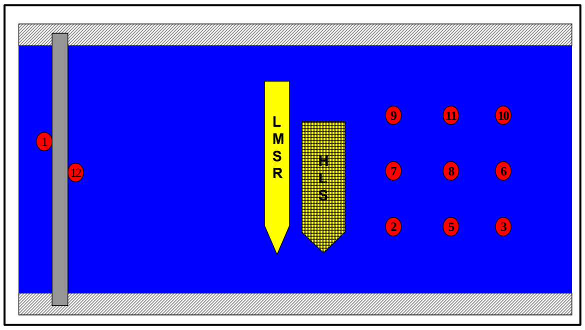
There were four different mooring types involved with this configuration, in order to gain an understanding of how the location of the HLS relative to the Ro/Ro Vessel affected the lee. Throughout the testing both the HLS and the Ro/Ro Vessel were moored to the sides of the tank using bow and stern lines, level with the surface of the water. The two vessels were moored together using a plastic fender to produce the separation, and a bungee line interweaved through a series of eyelets placed on both models. The size of the plastic fender used was reduced to run the reduced separation test.

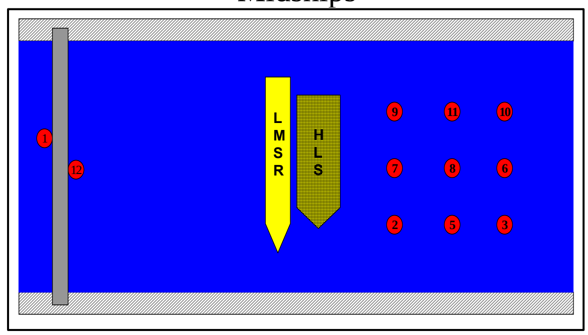




Sterns Level

Midships





Bows Level

Midships – Reduced Separation

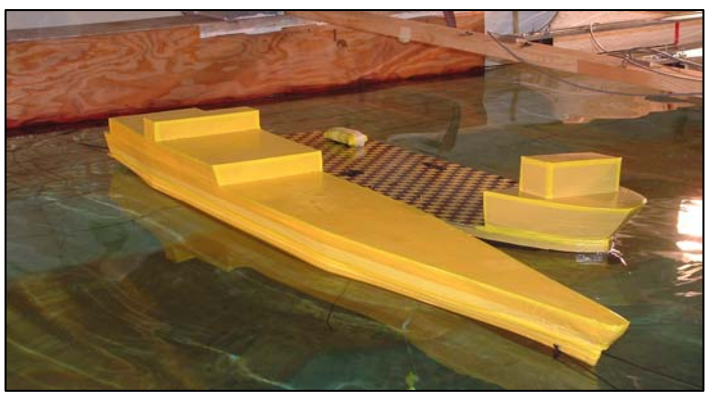
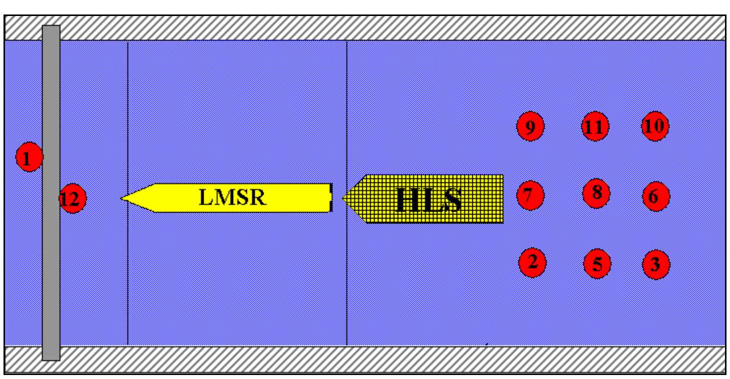


Figure 4 - Skin-to-Skin in Beam Seas Configuration



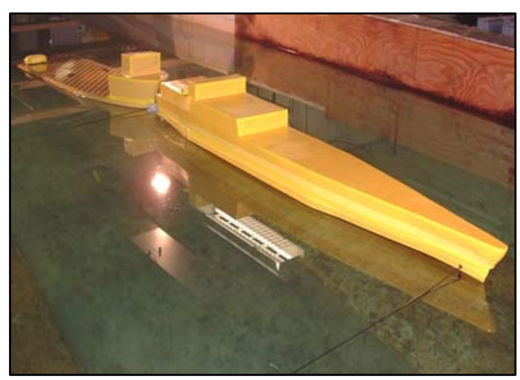


Figure 5 - Bow-to-Stern Configuration

Bow-to-Stern Configuration

The size of the lee directly behind the HLS was a focal point with the bow-to-stern configuration, Figure 5, along with characterizing the size and shape of the lee either side of the ships to observe what effect the formation has on the incident waves. During the testing period the HLS and the Ro/Ro ship were moored to each side of the tank using their bow mooring lines. To moor the two models together the pin joint used in previous testing was attached to the bow of the HLS. The HLS was trimmed throughout testing.

The bow-to-stern configuration would require the development and production of a purpose built modified HLS that would allow for resources and equipment to be offloaded through the bow of the ship and off via the stern or either side of the deck on the HLS.

Skin-to-Skin Configuration in Head Seas

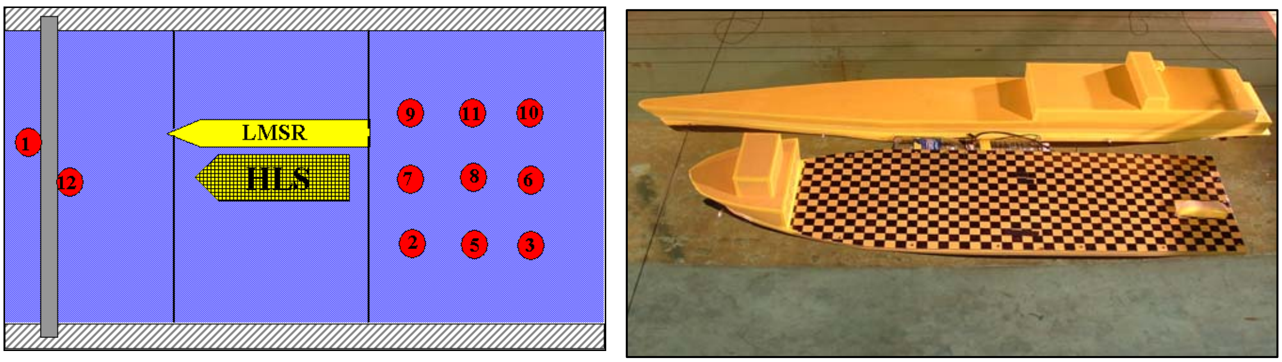


Figure 6 - Skin-to-Skin in Head Seas Configuration

This configuration, Figure 6, is similar to the skin-to-skin in beam seas test, but with both vessels facing bow on to the incident waves. Despite both vessels being aligned head to seas, their motions will differ and so the relative motion of the vessels was of particular interest.

Throughout the testing of this configuration the Ro/Ro ship was moored to the sides of the tank using the same bowlines as previously used, level with the surface of the water. The two models were moored together using a plastic fender to produce the separation and a bungee line interweaved through a series of eyelets placed on both models. Throughout the testing of this configuration the HLS was both trimmed and heeled.

Skin-to-Skin Configuration – Varied Angle from Incident Waves

The varied angle configuration was a test to conclude the effect of having the vessels at both 30° and 60° headings to the incident wave, and what kind of lee this would create. The probe positions for this configuration were not changed from previous testing, as illustrated in Figure 7.

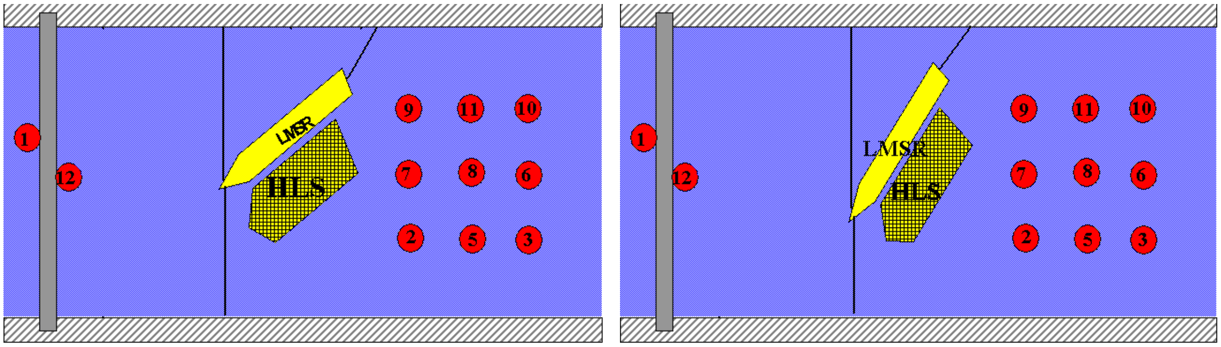


Figure 7 - Skin-to-Skin Configuration – 30° & 60° from Head Seas, respectively

The two models were moored by having the bowlines of the Ro/Ro ship attached to both sides of the tank and a single stern line on the Ro/Ro. The two models were moored to each other as described previously using the same plastic fender and a bungee line interweaved with a series of eyelets. The HLS was both trimmed and heeled for the duration of the experiment.

Confused Seas

As this was done with directional waves, a further area of consideration was what effect confused seas would have on the configurations. A number of the med-moor tests and skin-to-skin beam seas tests were repeated, but having confused seas incident upon the configuration. This was achieved by placing a large obstacle between the wavemaker and the first line of sonic wave probes upstream from the testing configuration.

Alterate Probe Positions

Probe locations were varied as shown in Figure 8 for the med-moor configuration in sea state 4 to increase resolution of the lee. A total of 108 readings were obtained.

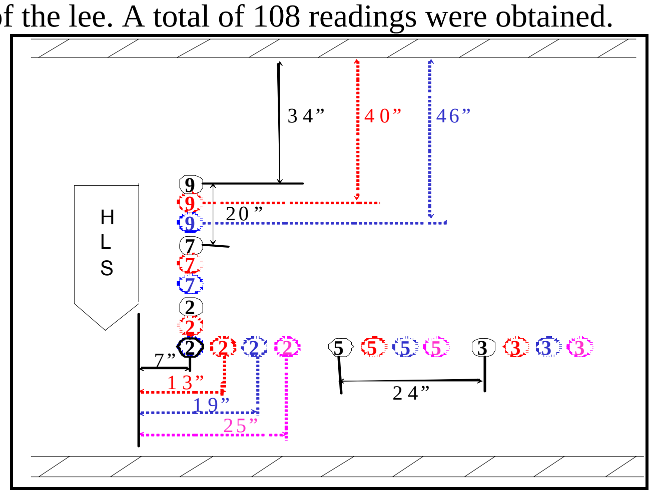


Figure 8 - Alternate Probe Locations

Test Matrix

In order to understand and ensure completion of all required testing, a test matrix was constructed. This detailed the number of configurations to be tested, the sea states to be tested in each configuration, and the modal period of each sea state.

Test Configuration	Test Variation	Configuration Number	Sea State				
			3	4	5	6	7
Med Moor	Tai An Kou	1	xxx	xxx	x	x	x
	Blue Marlin	2	xxx	xxx	x	x	x
	Blue Marlin (Varying Probe Position)	14		x			
	Blue Marlin (Confused Seas)	10	x	x	x		
Skin-to-Skin Beam Seas	Sterns level	3	x	x	x		
	Midships Level	4	xxx	xxx	x	x	x
	Midships Level (Reduced Separation)	13	x	x	x		
	Midships Level (Run 2)	12		x			
	Midships Level (Confused Seas)	11	x	x	x		
	Bows level	5	x	x	x		
Stern-to-Bow		6	xxx	xxx	x	x	x
Skin-to-Skin Head Seas		7	x	x	x	x	x
Skin-to-Skin Angled	30 Degree Angle	8	xxx	xxx	x	x	x
	60 Degree Angle	9	xxx	xxx	x	x	x

Table 1 - Test Matrix

DATA ACQUISITION

Sonic Probes

A series of sonic probes were used to measure the height of the waves in the tank during testing. A total of 11 probes were used, 2 being used to record the incident waves generated by the wavemaker, and the remaining 9 used to record the wave height in the lee. The sonic probes are connected to a control box that provides a power source and then allows the signal to be inputted into the DAQ card via a BNC adaptor.

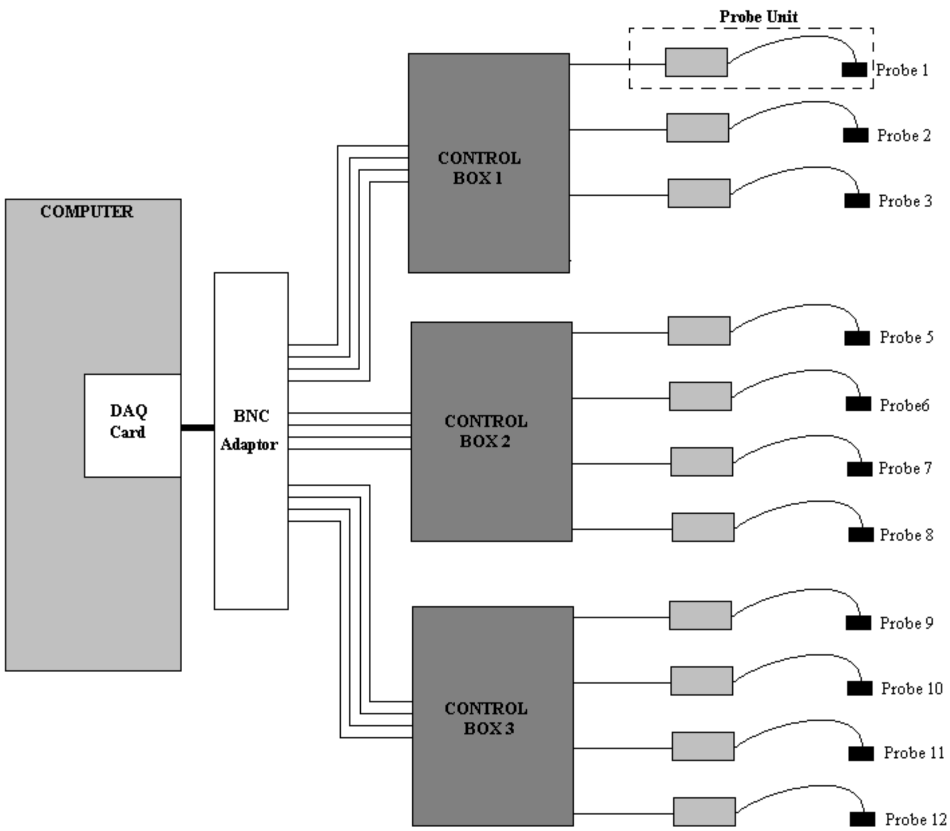


Figure 9 - Sonic Probes Schematic

The probes in the lee were fixed to a custom made frame that allowed their position to be fixed relative to each other, but with the flexibility of allowing movement along the length and breadth of the tank.

RESULTS AND ANALYSIS

Med-Moor Configuration

Figure 10 shows the med-moor configuration where the HLS is moored perpendicular to the stern of the Ro/Ro vessel. The Ro/Ro vessel is pointing into the direction of the incident waves. The lighters will be able to approach the deck of the HLS from the lee that is created by the configuration.

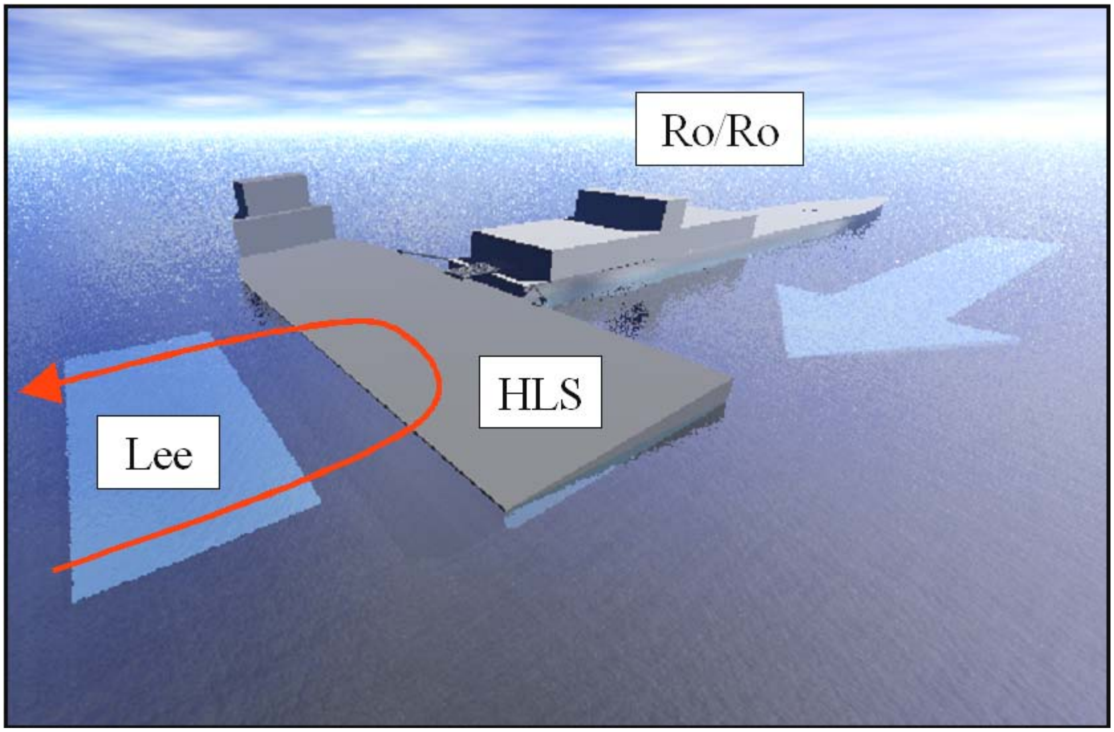


Figure 10 - Load/Off-load Path for Med-Moor Configuration

Reduction in Significant Wave Height

Figure 11 shows the reduction in significant wave height for two different sizes of HLS in the med-moor configuration. Phase I testing was carried out using a 1:158 scale model of the 50,000mt Tai An Kou HLS and was also used in Configuration 1 of Phase II testing. The second HLS used was the 100,000mt MV Blue Marlin, which was used in all of the remaining configurations tested in Phase II.

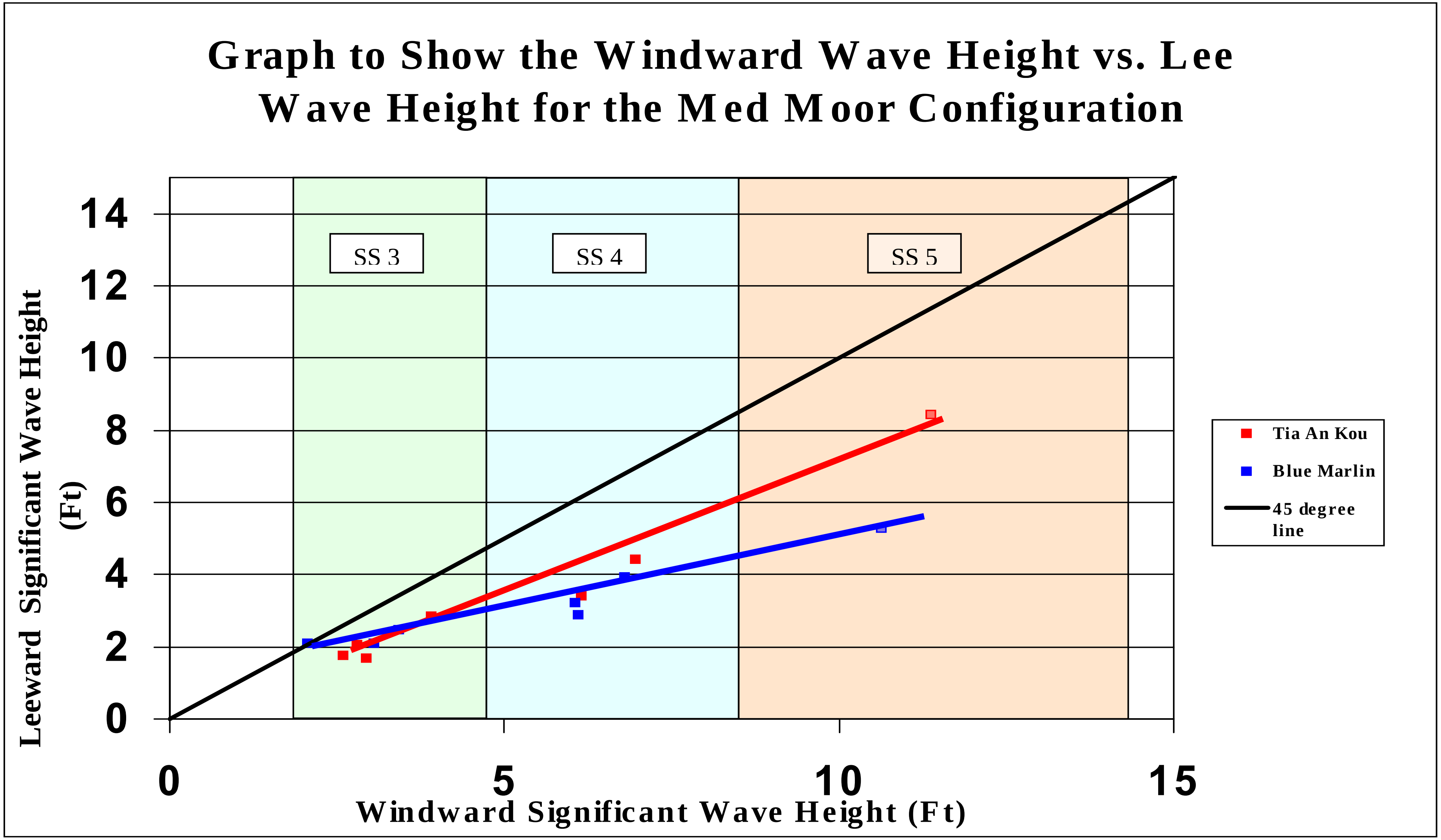


Figure 11 - Med-Moor Configuration Significant Wave Height Comparison

Confused Seas

The Med-Moor configuration with the MV Blue Marlin was run in confused seas. The results show that the reduction in significant wave height in the lee and the size of the lee did not vary extensively from the tests completed without confused seas.

Throughput

The med-moor configuration would seem to give a high level of throughput for a number of reasons:

- **The Ramp**
  The med-moor arrangement utilizes the stern ramp, whereas the skin-to-skin arrangement relies on the side ramp to transfer equipment to the deck of the HLS.

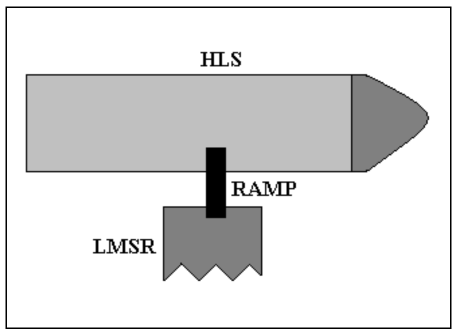


Figure 12 - Stern Ramp

Figure 12 shows how the stern ramp impacts the usable deck area of the HLS in the med-moor configuration. The figure shows clearly that the ramp in the med-moor configuration allows for a high portion of usable deck area, whilst also negating the need for several tight turns that will affect how quickly the equipment can be transferred between ships.

Another factor to consider is that ships with only a stern ramp will be limited to the med-moor configuration.

- **LCAC loading**
  The med-moor configuration allows for a number of LCACs to simultaneously approach and board the HLS from its leeward side.

Ramp Torsion

The testing showed that with the med-moor configuration there were no visible torsional effects on the ramp, since both edges of the ramp stayed in contact with the deck of the HLS at all times up to sea state 5.

Mooring Experience

Commercial experience with med-moor is limited to harbors, however such practice is rarely used by the military.

Development of an ITS for seabasing operations requires extension of med-moor experience into higher sea states.

Skin-to-Skin – Beam Seas

Figure 13 shows the Ro/Ro vessel and HLS in the skin-to-skin configuration in beam seas. The HLS is heeled and trimmed to facilitate the boarding of an LCAC on to the HLS from the stern, and then to exit from the side of the HLS.

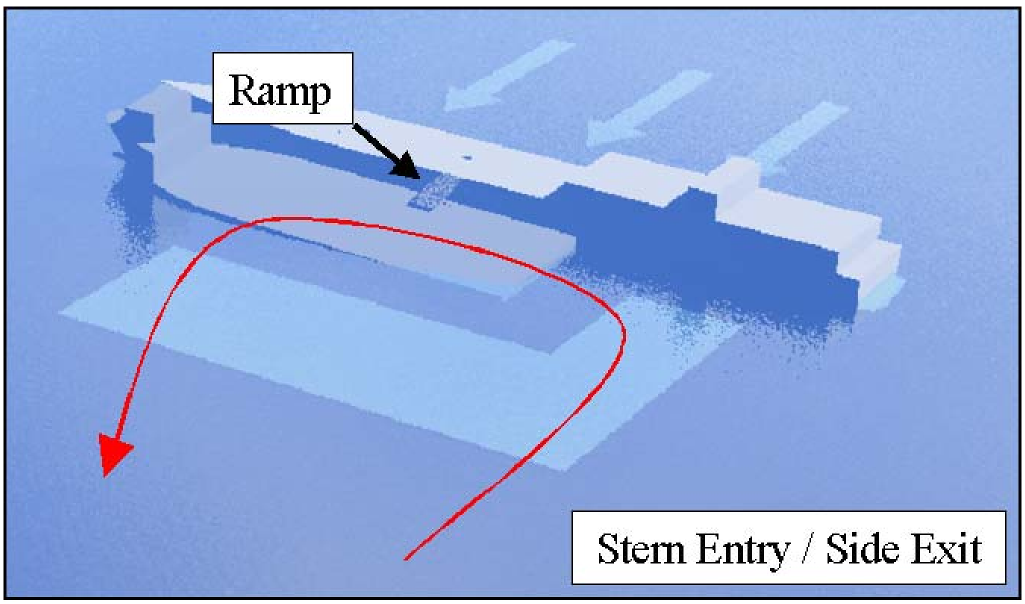


Figure 13 - Load/Off-load Path for Skin-to-Skin in Beam Seas Configuration

Relative Position of the HLS

The testing looked at mooring the HLS in three different positions relative to the Ro/Ro ship. By mooring the two ships with their bows level as shown in Figure 13, the Ro/Ro vessel creates a lee at the stern of the HLS. This allows the LCACs to board the HLS in calmer water.

From the test results there is no significant difference in the lee created by the HLS, as shown in Appendix C for configurations 3, 4, and 5. Therefore, for a high throughput requirement involving LCACs the configuration in Figure 13 is recommended.

Heading of the HLS and Ro/Ro

The ships are ideally perpendicular to the direction of the waves. If the angle is reduced to 60° then the reduction in significant wave height is increased at the stern and reduced at the bow of

the HLS. The problem with this reduced angle is the relative motions of the two ships, with a coupling of pitch and roll leading to torsional loading on the ramp. Therefore a heading of between 75° and 90° to the direction of the waves is desirable.

Characterization of the Lee

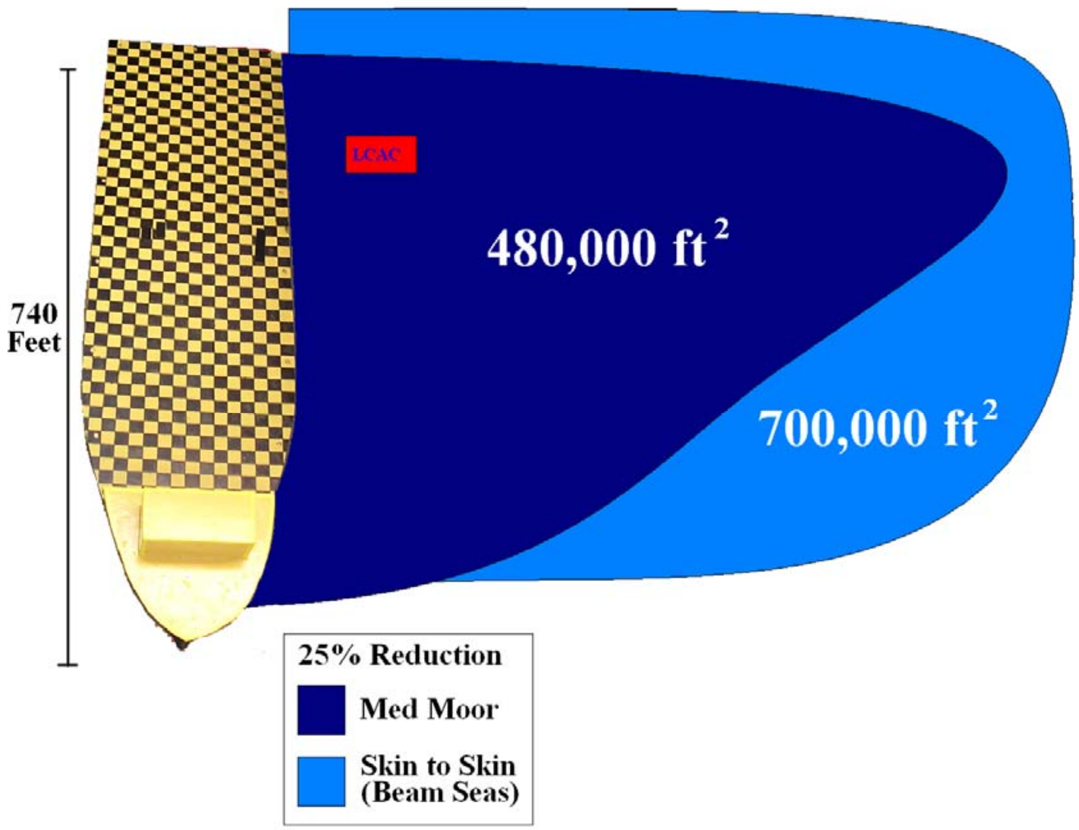


Figure 14 - Comparison of Lee Size

Figure 14 shows the size of the lee (defined here as a 25% Reduction in significant wave height) relative to the HLS for both the med-moor configuration featuring the MV Blue Marlin, and the Skin-to-Skin configuration at beam seas. The Skin-to-Skin configuration shows a greater lee in terms of area covered with 700,000 ft^2, compared to the 480,000 ft^2 lee produced by the med-moor configuration.

Confused Seas

The skin-to-skin configuration in beam seas with midships level was also run in confused seas. The results show that the reduction in significant wave height in the lee, and the size of the lee did not vary extensively from the tests completed without confused seas.

These results illustrate that the test setup used, where the wavemaker produces uniform irregular waves, is a suitable arrangement.

Throughput

The skin-to-skin configuration would seem to give a reduced level of throughput for a number of reasons:

- **The Ramp**

  The skin-to-skin arrangement relies on the side ramp to transfer equipment to the deck of the HLS.

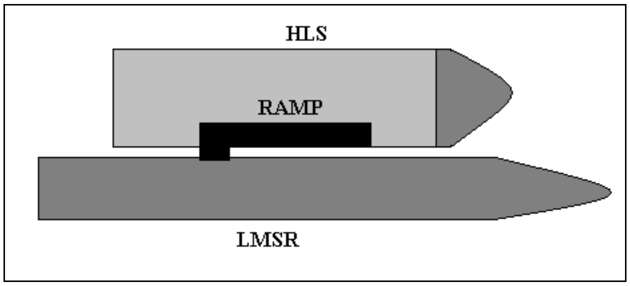


Figure 15 - Side Ramp

Figure 15 shows how the side ramp affects the usable deck area in the skin-to-skin configuration. The figure indicates that the side ramp in the skin-to-skin configuration will have a more significant impact on the usable deck area than the stern ramp in the med-moor configuration, whilst also requiring vehicles to negotiate several tight turns that will affect how quickly the equipment can be transferred between ships.

- **LCAC loading**

  The skin-to-skin configuration allows for only one or two LCACs to approach from the stern of the HLS at one time, again reducing the throughput rate.

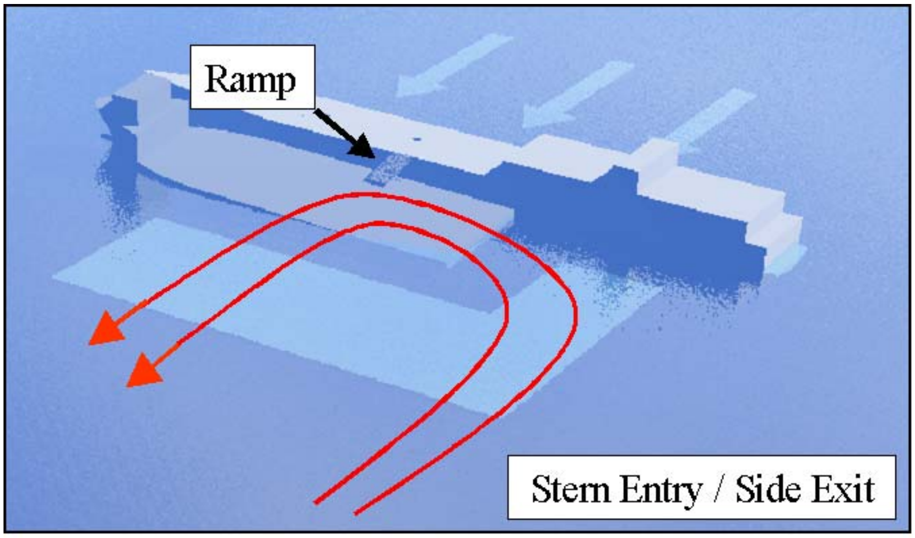


Figure 16 - Throughput for Skin-to-Skin Configuration

Ramp Torsion

The testing showed that with the skin-to-skin configuration in beam seas the two vessels experienced differential roll. This differential roll will cause a significant amount of torsion on the ramp.

The testing also showed that when the skin-to-skin configuration was rotated by 30° and 60° a coupling of pitch and roll was observed. These motions will emphasize the detrimental effect on the ramp. Therefore, if the skin-to-skin configuration in beam seas is not aligned to the direction of the waves there will be increased torsion on the ramp.

Mooring Experience

Commercial and military experience with skin-to-skin is practiced in harbors, at sea in calm environments between stationary platforms, and between slowly moving ships in benign seas. Commercial skin-to-skin operations are practiced in higher sea states as well in the petroleum and offshore industries.

Development of an ITS for seabasing operations requires extension of skin-to-skin experience into higher sea states.

Skin-to-Skin Head Seas

The skin-to-skin configuration (Configuration 7), shown in Figure 17, showed a large reduction in the significant wave height within the lee of the HLS and the Ro/Ro Vessel.

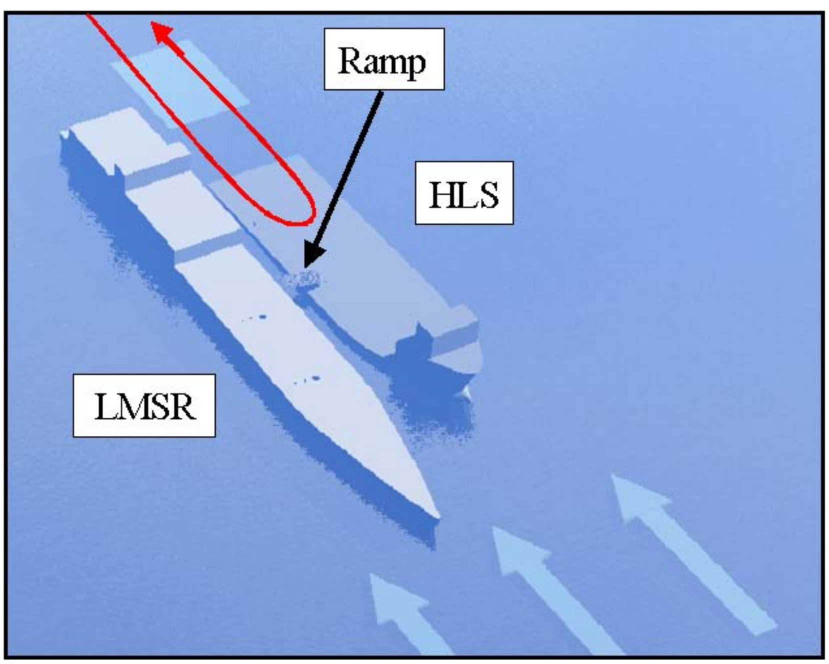


Figure 17 - Load/Off-load Path for Skin-to-Skin in Head Seas Configuration

Figure 18 shows the percentage change in significant wave height for configuration 7 in sea states 4 and 5. The graph shows that there is a 50% reduction in significant wave height directly behind the HLS and the Ro/Ro ship, however this reduction falls off dramatically on the open side of the HLS.

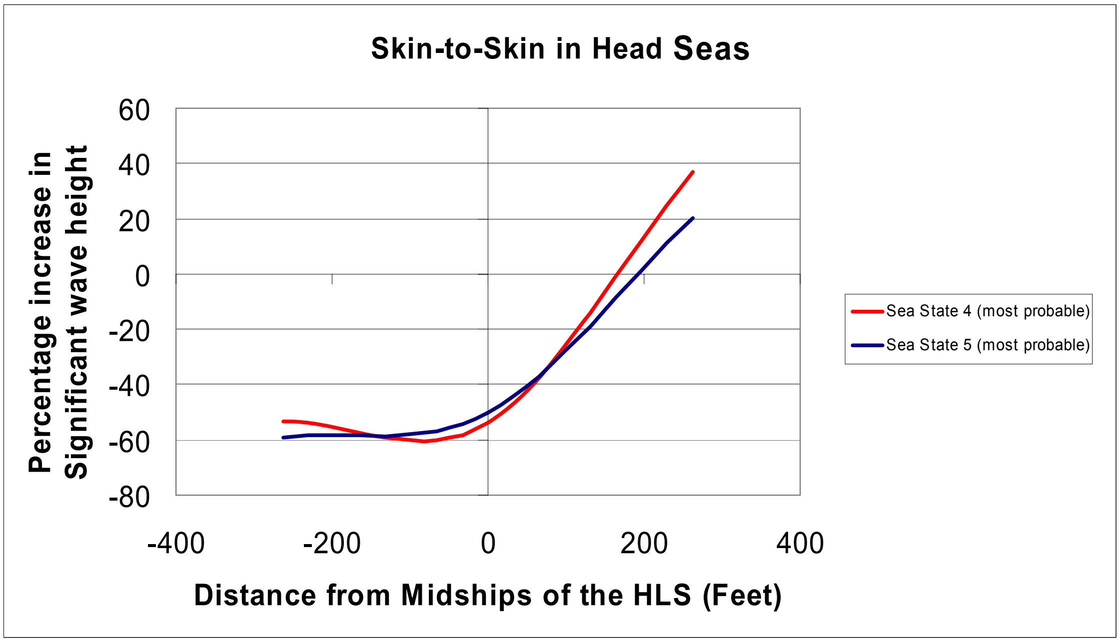


Figure 18 - Skin-to-Skin in Head Seas Wave Height Analysis

The results show that the lee extends well beyond the HLS directly behind the two vessels. The skin-to-skin configuration in head seas is not seen as a viable alternative due to its relatively small lee that may limit the approach of lighters, therefore reducing the throughput that can be achieved. An LCAC would be required to embark and disembark the deck of the HLS from the stern.

Bow-to-Stern

The bow-to-stern configuration (Configuration 6), shown in Figure 19, showed a large reduction in significant wave height within the lee of the HLS.

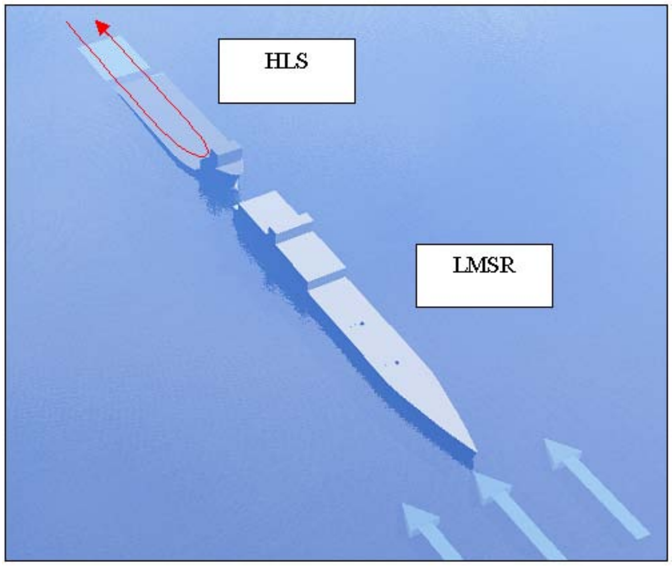


Figure 19 - Load/Off-load Path for Bow-to-Stern Configuration

The results show that the lee extends well beyond the HLS directly behind the HLS, but drops off significantly either side of the HLS producing a very narrow lee. This reduction can be seen clearly in Figure 20 with virtually no reduction 250 feet either side of the middle of the HLS.

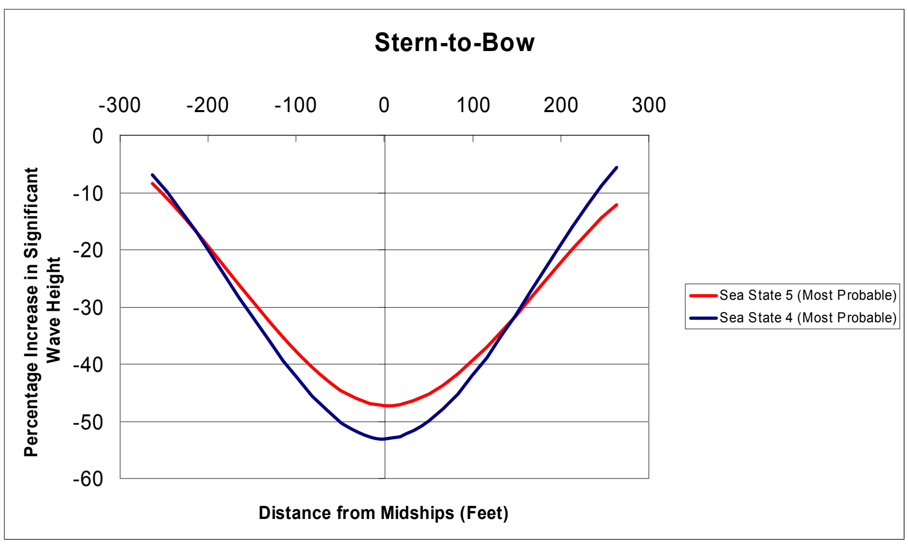


Figure 20 - Bow-to-Stern Configuration Wave Height Analysis

The bow-to-stern configuration is not seen as a viable alternative due to its relatively small lee that may limit the approach of lighters, therefore reducing the throughput that can be achieved. The other disadvantage of this configuration is that a modified HLS may be required as few existing HLSs have the capability to accommodate the transfer of vehicles through the bow of the ship and these ships may not be suitable in other ways as an ITS.

Mooring Issues

There are a number of issues involved with the med-moor and skin-to-skin configurations that need to be addressed for the ITS concept.

Med-moor

The ITS concept calls for the capability to operate in deep water, however a shallow water capability has also been considered in the near term.

- **Deep Water Capability**
    - Docking System Design
        - Lines
        - Forces
        - Winches (Constant Tension)
        - Procedures
    - Virtual Dynamic Positioning Design
        - Thruster Sizes
        - Integration
    - Development of Standard Operating procedures (SOP's)

- **Near Term Shallow Water Capability**
    - Docking System Design
        - Lines
        - Forces
        - Winches (Constant Tension)
        - Procedures
    - ITS Anchor System
    - Integration of line tension with propulsion, thrusters and the environment.
    - Development of Standard Operating procedures (SOP's)

Skin-to-Skin

- Docking System Design
    - Lines
    - Forces
    - Winches (Constant Tension)
    - Procedures
- Development of Standard Operating procedures (SOP's)

CONCLUSION

The four configurations that were tested were compared by the extent of lee created, the reduction in wave height in the lee, relative motions, deck wash observed, and torsional loading on the ramp. Throughout testing no deck wash was observed in any configuration until sea state 6. Each configuration showed a significant reduction in wave height in the lee, but with varying characteristics in each case.

Skin-to-Skin

The skin-to-skin configurations were tested in a variety of headings and the following observations were made:

Head Seas

- A 50-60% reduction in significant wave height is achieved, however the area covered by this lee is less significant compared to the skin-to-skin beam seas and the med-moor configuration.
- The lee created is located at the stern of the two vessels; either side of the ship is still unprotected.
- A significant amount of torsional loading is applied to the side ramp.
- Due to the size and arrangement of the side ramp, the configuration has a limited level of throughput efficiency, due to the impact on the available deck area on the HLS.
- Development of a ITS for seabasing operations requires extension of skin-to-skin experience into higher sea states.
- The side ramp also impacts the amount of usable deck area.

Beam Seas

- This configuration produced the largest lee (50% greater than the med-moor configuration). In addition the reduction in wave height was similar to the med-moor configuration.
- Skin-to-skin is a more established mooring configuration.
- Torsional loading on the side ramp is an issue.
- Due to the size and potential arrangement of the side ramp, the configuration may limit throughput efficiency, due to the impact on the available deck area on the HLS.
- If a stern loading/side-offloading maneuver for embarking LCACs is employed then the throughput rate is reduced, when compared to side embarkation of LCACs.

This configuration demonstrates a number of notable advantages.

Quartering Seas

- A 20% reduction in significant wave height is achieved, however the area covered by this lee is less significant compared to the skin-to-skin configuration in beam seas.
- A coupling of pitch and roll were observed in most cases. This would lead to torsional loading on the ramp.
- Development of a ITS for seabasing operations requires extension of skin-to-skin experience into higher sea states.
- Due to the size and arrangement of the side ramp, the configuration has a limited level of throughput efficiency, due to the impact on the available deck area on the HLS.

Bow-to-Stern

The analysis of the bow-to-stern configuration produced a number of key issues:

- A large reduction in significant wave height is accomplished, however the extent of this lee is the smallest of all configurations tested.
- No significant torsional loading on the stern ramp.
- The configuration has a particularly poor throughput rate, governed by the primary means of loading/offloading taking place at the stern of the HLS.

Med-Moor

Testing of the med-moor configuration produced the following conclusions:

- This configuration produced a large lee and a 33% reduction in the significant wave height in the lee.
- When considering the combination of Ro/Ro vessel pitch and HLS roll, the torsional loading on the stern ramp is minimized.
- The configuration allows for an excellent throughput rate, greater than is expected for the skin-to-skin configuration.
- Development of a ITS for seabasing operations requires extension of med-moor experience into higher sea states.

Conclusion

The completion of Phase II testing has highlighted both the Med-Moor and Skin-to-Skin in beam seas configurations to be the most advantageous. The primary factors in constructing this conclusion are the size of the lee and the reduction in wave height that these configurations produce. This testing de-risks the ITS concept further and recommends the need to conduct full scale progressive and instrumented trials. Development of a ITS for seabasing operations requires extension of skin-to-skin and/or med-moor experience into higher sea states.

RECOMMENDATIONS

The size of the models used in testing precluded the use of additional instrumentation. It would be useful to record data regarding the characteristics of the two models during testing, particularly in understanding the conditions that would be experienced on the deck of the HLS.

Similarly, the size of tank and wavemaker limits the number of waves that can be produced and tested. To have larger models, placed in a larger tank with the facility for multi-directional waves would produce invaluable results on how the lee is affected.

Throughout testing the probes were positioned to record the incident wave height upstream and downstream of the configurations. It would have been useful to position probes in line with the configuration to understand how the vessels were deflecting the incident waves.

The varying of probe positions during testing provided 108 data readings, and proved to be extremely useful in quantifying the characteristics of the lee. If the tests were to be repeated then it would prove very useful to obtain similar readings for more than one configuration, and more than one sea state.

The calibration process that was carried out before introducing any models into the testing environment was critical to providing credible results. More extensive calibration is recommended for any similar testing.

FURTHER WORK

The completion of Phase II testing has provided further de-risking of the ITS concept. A number of the recommendations have been focused on the size of the subscale testing. To continue testing of the ITS concept an at-sea demonstration would prove invaluable, and provide the opportunity to attain full-scale data on ship motions and lee characteristics.

REFERENCES

[1.] V. Lewis, Editor, "Principles of Naval Architecture," Volume III Motions in Waves and Controllability, The Society of Naval Architects and Marine Engineers, © 1989
[2.] www.capitol.northgrum.com/programs/sealift.html

APPENDICES

Appendix A – Calibration

Calibration Runs

A number of calibration runs were completed with no models in the tank. The significant wave height of the upstream probes (Probes 1 and 12) were recorded and compared to nine downstream probes (Probes 2,3,5,6,7,8,9,10 & 11). The results are shown in Figure 21.

		Significant Wave Height (Inches)										
Sea State	Modal Period	Probe 1	Probe 2	Probe 3	Probe 5	Probe 6	Probe 7	Probe 8	Probe 9	Probe 10	Probe 11	Probe 12
3	10% Below MP	0.2112	0.1776	0.0899	0.1209	0.1269	0.1305	0.1426	0.1249	0.1419	0.1223	0.1636
3	10% Below MP	0.2111	0.1387	0.0950	0.1269	0.1323	0.1467	0.1367	0.1302	0.1432	0.1199	0.1745
3	10% Below MP	0.1342	0.0713	0.0545	0.1058	0.1465	0.1194	0.0878	0.1804	0.1078	0.0784	0.1361
3	Most Probable	0.1678	0.1566	0.0786	0.1392	0.1282	0.1659	0.1149	0.1187	0.1324	0.1361	0.1522
3	Most Probable	0.2106	0.1698	0.1602	0.2508	0.1718	0.1924	0.1630	0.1894	0.1863	0.1740	0.2014
3	Most Probable	0.2709	0.1933	0.1865	0.1818	0.2171	0.2533	0.2128	0.2360	0.2432	0.2247	0.2690
3	Most Probable	0.2246	0.1865	0.1652	0.1812	0.1780	0.1924	0.2001	0.2139	0.2182	0.2002	0.2405
3	10% Above MP	0.1914	0.1672	0.1248	0.1717	0.1669	0.1924	0.1771	0.1710	0.1694	0.1574	0.1908
3	10% Above MP	0.1492	0.1541	0.1130	0.1229	0.1673	0.1539	0.1372	0.1728	0.1373	0.1168	0.1430
3	10% Above MP	0.1650	0.1281	0.1068	0.1292	0.1868	0.1508	0.1498	0.1884	0.1465	0.1339	0.1536
4	10% Below MP	0.2721	0.2645	0.2366	0.2248	0.2533	0.2201	0.2492	0.2689	0.2463	0.2409	0.2733
4	10% Below MP	0.4650	0.4669	0.4337	0.4001	0.3709	0.3730	0.3809	0.3884	0.3870	0.3825	0.4471
4	Most Probable	0.2826	0.2270	0.2013	0.2370	0.2204	0.2427	0.2224	0.2505	0.2580	0.2239	0.2827
4	Most Probable	0.4237	0.2992	0.2712	0.2709	0.2831	0.3040	0.2887	0.2936	0.2913	0.2741	0.4286
4	Most Probable	0.5584	0.5582	0.5344	0.4895	0.4842	0.4765	0.5031	0.4720	0.4776	0.4917	0.5547
4	Most Probable	0.3199	0.3054	0.2909	0.2723	0.3053	0.2795	0.2962	0.2915	0.2960	0.2899	0.3393
4	Most Probable	0.4247	0.4441	0.4101	0.3899	0.4028	0.3948	0.4096	0.4000	0.3926	0.4138	0.4537
4	10% Above MP	0.3720	0.2509	0.2297	0.2524	0.2529	0.2696	0.2445	0.2694	0.2771	0.2520	0.3384
4	10% Above MP	0.3355	0.3295	0.2724	0.2685	0.3129	0.3185	0.2791	0.3201	0.2979	0.2889	0.3310
5	Most Probable	0.9451	0.7369	0.6952	0.6732	0.6829	0.7548	0.7389	0.6652	0.7150	0.6372	0.9715
5	Most Probable	1.0976	1.0186	0.9233	0.9109	1.0537	1.0068	1.0158	0.8970	0.8979	0.8649	1.1048
5	Most Probable	0.8251	0.7514	0.6528	0.6602	0.6683	0.6422	0.7104	0.6270	0.6053	0.6177	0.7992
6	Most Probable	2.3501	2.0366	1.9386	1.8763	1.9268	1.9176	2.0705	1.9076	1.9300	1.7867	2.2300
6	Most Probable	1.2533	1.1608	1.1268	1.0999	1.1492	1.1200	1.2706	1.1359	1.1834	1.0874	1.1843

Figure 21 - Calibration Significant Wave Height Results

Based on these results a calibration factor is calculated for each sea state condition for each of the probes used to measure the lee.

		Calibration Factors								
Sea State	Modal Period	Probe 2	Probe 3	Probe 5	Probe 6	Probe 7	Probe 8	Probe 9	Probe 10	Probe 11
3	10% Below MP	0.8364	0.6000	0.7164	0.8222	0.8058	0.7553	0.8995	0.8028	0.6607
3	Most Probable	0.8302	0.6676	0.8851	0.8011	0.9341	0.7896	0.8639	0.8927	0.8471
3	10% Above MP	0.9114	0.6991	0.8503	1.0637	1.0024	0.9355	1.0868	0.9154	0.8213
4	10% Below MP	0.9969	0.9092	0.8509	0.8711	0.8125	0.8744	0.9188	0.8758	0.8611
4	Most Probable	0.8892	0.8250	0.8136	0.8315	0.8351	0.8400	0.8438	0.8493	0.8281
4	10% Above MP	0.8475	0.7320	0.7582	0.8254	0.8573	0.7628	0.8595	0.8370	0.7882
5	Most Probable	0.8731	0.7893	0.7809	0.8308	0.8309	0.8561	0.7602	0.7689	0.7370
6	Most Probable	0.9209	0.8855	0.8609	0.8921	0.8781	0.9733	0.8825	0.9068	0.8362
7	Most Probable	0.9209	0.8855	0.8609	0.8921	0.8781	0.9733	0.8825	0.9068	0.8362

Figure 22 - Sea State Calibration Factors

Appendix B – Results Tables

Configuration 1

Med-Moor Configuration with Tai An Kou

Run Number	Sea State	Wave Height (Inches)										
		1	2	3	5	6	7	8	9	10	11	12
0	3 (10% less than MP)	0.2047	0.2523	0.1318	0.1597	0.1541	0.1089	0.1478	0.1761	0.1415	0.1433	0.1889
1	3 (Most probable)	0.2190	0.2202	0.1174	0.1533	0.1785	0.1464	0.1643	0.1713	0.1354	0.1384	0.2058
2	3 (!0% above MP)	0.2203	0.2550	0.1448	0.1603	0.1601	0.1294	0.2205	0.1772	0.1747	0.1572	0.2263
3	4 (10% less than MP)	0.3055	0.2752	0.1849	0.2051	0.1782	0.1761	0.2435	0.2124	0.1663	0.1644	0.2892
4	4 (Most probable)	0.4652	0.3924	0.2769	0.2843	0.3013	0.2167	0.2952	0.3185	0.2875	0.2612	0.4689
5	4 (!0% above MP)	0.5088	0.5027	0.3593	0.3434	0.4206	0.2884	0.3961	0.3860	0.3644	0.3361	0.5475
6	5 (Most probable)	0.8640	0.8772	0.5878	0.6298	0.7295	0.5313	0.6781	0.7306	0.5458	0.5800	0.8636
7	6 (Most probable)	1.3042	1.0228	1.0065	1.1714	1.1168	1.0055	1.0566	1.0111	0.9771	1.1229	1.1483

Table 2 – Raw Results for Configuration 1

	Wave Height (Feet)										
Sea tate S	1	2	3	5	6	7	8	9	10	11	12
3 (10% less than MP)	2.6946	3.9720	2.8914	2.9348	2.4679	1.7789	2.5769	2.5778	2.3215	2.8561	2.4873
3 (Most probable)	2.8831	3.4919	2.3147	2.2799	2.9338	2.0641	2.7391	2.6114	1.9976	2.1514	2.9793
3 (!0% above MP)	2.9003	3.6832	2.7272	2.4827	1.9814	1.6994	3.1036	2.1470	2.5132	2.5196	3.8081
4 (10% less than MP)	4.0231	3.6351	2.6769	3.1730	2.6931	2.8537	3.6661	3.0437	2.5002	2.5135	3.8081
4 (Most probable)	6.1249	5.8102	4.4192	4.6012	4.7719	3.4164	4.6271	4.9701	4.4568	4.1529	6.1737
4 (!0% above MP)	6.6994	7.8102	6.4630	5.9634	6.7089	4.4289	6.8373	5.9131	5.7319	5.6154	7.2081
5 (Most probable)	11.3762	13.2292	9.8064	10.6194	11.5620	8.4192	10.4288	12.6526	9.3461	10.3626	11.3710
6 (Most probable)	17.1718	14.6246	14.9663	17.9158	16.4824	15.0767	14.2938	15.0851	14.1859	17.6827	15.1195

Table 3 – Calibrated and Scaled Results for Configuration 1

Configuration 2

Med-Moor Configuration with MV Blue Marlin

Run Number	Sea State	Wave Height										
		1	2	3	5	6	7	8	9	10	11	12
8	3 (10% less than MP)	0.1565	0.1052	0.0680	0.1219	0.1181	0.1285	0.1250	0.1005	0.1208	0.1227	0.1562
9	3 (Most probable)	0.2411	0.1503	0.1311	0.1646	0.1665	0.1484	0.1850	0.1508	0.1617	0.1438	0.2240
11	3 (!0% above MP)	0.2824	0.1704	0.1622	0.1881	0.2445	0.1873	0.2675	0.1992	0.1788	0.1655	0.2361
15	4 (10% less than MP)	0.4824	0.3198	0.2697	0.3199	0.3256	0.1775	0.2929	0.2676	0.2544	0.2629	0.4439
16	4 (Most probable)	0.4701	0.3603	0.3150	0.3611	0.3412	0.2046	0.2864	0.2977	0.2881	0.2842	0.4495
17	4 (!0% above MP)	0.5071	0.4044	0.3435	0.3761	0.4186	0.2554	0.3480	0.3309	0.3186	0.3393	0.5253
18	5 (Most probable)	0.7795	0.6544	0.5366	0.4843	0.5855	0.3338	0.5753	0.5050	0.4234	0.4565	0.8350
19	6 (Most probable)	1.2835	1.0663	0.9744	0.8987	1.0156	0.8392	0.9688	1.0198	0.8827	0.8545	1.2474
69	7 (Most probable)	1.7341	1.4681	1.2493	1.2902	1.4010	1.1051	1.5528	1.4184	1.3438	1.3531	1.7818

Table 4 – Raw Results for Configuration 2

	Wave Height (feet)										
Sea State	1	2	3	5	6	7	8	9	10	11	12
3 (10% less than MP)	2.0611	1.6566	1.4922	2.2401	1.8908	2.0999	2.1792	1.4714	1.9814	2.4444	2.0565
3 (Most probable)	3.1745	2.3844	2.5849	2.4489	2.7373	2.0923	3.0854	2.2990	2.3856	2.2346	3.1081
3 (!0% above MP)	3.7180	2.4623	3.0551	2.9129	3.0260	2.4600	3.7648	2.4134	2.5714	2.6541	5.8447
4 (10% less than MP)	6.3521	4.2239	3.9057	4.9505	4.9213	2.8768	4.4109	3.8343	3.8245	4.0197	5.8447
4 (Most probable)	6.1891	5.3353	5.0272	5.8442	5.4032	3.2260	4.4891	4.6460	4.4670	4.5180	5.9179
4 (!0% above MP)	6.6765	6.2818	6.1781	6.5306	6.6771	3.9220	6.0069	5.0685	5.0123	5.6687	6.9162
5 (Most probable)	10.2636	9.8686	8.9527	8.1661	9.2789	5.2898	8.8480	8.7458	7.2497	8.1557	10.9937
6 (Most probable)	16.8994	15.2453	14.4891	13.7450	14.9893	12.5826	13.1051	15.2162	12.8155	13.4562	16.4235
7 (Most probable)	22.8322	20.9907	18.5753	19.7323	20.6778	16.5704	21.0061	21.1630	19.5115	21.3071	23.4604

Table 5 – Calibrated and Scaled Results for Configuration 3

Configuration 3

Skin-to-Skin Configuration – Beam Seas with Sterns Level

Run Number	Sea State	Wave Height										
		1	2	3	5	6	7	8	9	10	11	12
21	3 (Most probable)	0.2267	0.2625	0.1160	0.1312	0.1468	0.1453	0.1395	0.1294	0.1548	0.1264	0.2483
22	4 (Most probable)	0.5616	0.2967	0.2883	0.3480	0.3141	0.3069	0.2493	0.2818	0.2507	0.2304	0.4785
24	5 (Most probable)	0.5623	0.2401	0.2777	0.2980	0.2633	0.2302	0.2714	0.2058	0.2107	0.1668	0.5031

Table 6 – Raw Results for Configuration 3

Wave Height (Feet)											
Sea State	1	2	3	5	6	7	8	9	10	11	12
3 (Most probable)	2.9844	4.1623	2.2882	1.9510	2.4130	2.0474	2.3263	1.9728	2.2829	1.9651	3.2696
4 (Most probable)	7.3947	4.3929	4.6011	5.6318	4.9733	4.8390	3.9080	4.3970	3.8862	3.6628	6.3000
5 (Most probable)	7.4042	3.6209	4.6326	5.0253	4.1728	3.6486	4.1740	3.5636	3.6088	2.9796	6.6243

Table 7 – Calibrated and Scaled Results for Configuration 3

Configuration 4

Skin-to-Skin Configuration – Beam Seas with Midships Level

Run Number	Sea State	Wave Height										
		1	2	3	5	6	7	8	9	10	11	12
25	3 (10% less than MP)	0.2492	0.0772	0.0834	0.1300	0.1251	0.1050	0.1568	0.1458	0.1343	0.1207	0.2237
26	3 (Most probable)	0.2879	0.1774	0.1104	0.1394	0.1535	0.1242	0.1357	0.1371	0.1368	0.1332	0.2540
27	3 (!0% above MP)	0.2243	0.1051	0.1052	0.1430	0.1476	0.1550	0.1641	0.1407	0.1354	0.1284	0.2366
28	4 (10% less than MP)	0.3337	0.2258	0.2083	0.1946	0.2443	0.1676	0.2248	0.1858	0.1629	0.2062	0.3855
29	4 (Most probable)	0.5694	0.3452	0.3085	0.3001	0.3403	0.2836	0.3101	0.2682	0.2361	0.2465	0.4577
30	4 (!0% above MP)	0.5120	0.3361	0.3050	0.3091	0.3880	0.3416	0.3625	0.2667	0.2900	0.2782	0.5251
31	5 (Most probable)	0.8384	0.5062	0.4109	0.4242	0.6278	0.4892	0.5792	0.3633	0.3545	0.4175	0.7392
32	6 (Most probable)	1.2678	0.9780	0.9806	0.8541	1.1056	0.8333	1.0737	0.8513	0.9570	0.8179	1.3094
33	7 (Most probable)	1.7572	1.3240	1.3737	1.2655	1.6009	1.2150	1.6523	1.2942	1.3595	1.2141	1.7124

Table 8 – Raw Results for Configuration 4

Wave Height (feet)											
Sea tate S	1	2	3	5	6	7	8	9	10	11	12
3 (10% less than MP)	3.2810	1.2161	1.8307	2.3889	2.0038	1.7163	2.7335	2.1338	2.2029	2.4062	2.9453
3 (Most probable)	3.7907	2.8141	2.1769	2.0738	2.5222	1.7512	2.2623	2.0892	2.0171	2.0711	3.1149
3 (!0% above MP)	2.9532	1.5183	1.9807	2.2138	1.8272	2.0362	2.3092	1.7050	1.9475	2.0586	5.0758
4 (10% less than MP)	4.3933	2.9826	3.0167	3.0118	3.6920	2.7162	3.3851	2.6624	2.4489	3.1531	5.0758
4 (Most probable)	7.4972	5.1110	4.9240	4.8574	5.3894	4.4720	4.8611	4.1852	3.6598	3.9200	6.0268
4 (!0% above MP)	6.7417	5.2214	5.4868	5.3668	6.1892	5.2460	6.2565	4.0850	4.5619	4.6468	6.9139
5 (Most probable)	11.0395	7.6345	6.8544	7.1536	9.9498	7.7528	8.9087	6.2925	6.0705	7.4589	9.7325
6 (Most probable)	16.6933	13.9835	14.5803	13.0627	16.3171	12.4943	14.5246	12.7017	13.8951	12.8788	17.2399
7 (Most probable)	23.1363	18.9305	20.4261	19.3542	23.6282	18.2183	22.3514	19.3095	19.7386	19.1172	22.5464

Table 9 – Calibrated and Scaled Results Results for Configuration 4

Configuration 5

Skin-to-Skin Configuration – Beam Seas with Bows Level

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
34	3 (Most probable)	0.2388	0.2140	0.1007	0.1235	0.1493	0.1260	0.1242	0.1445	0.1243	0.1413	0.2224
35	4 (Most probable)	0.5675	0.2864	0.1991	0.1931	0.2578	0.2908	0.2978	0.2294	0.2065	0.2055	0.5107
36	5 (Most probable)	0.8477	0.4707	0.3992	0.4428	0.5579	0.3752	0.4882	0.4722	0.3718	0.3969	0.7854

Table 10 – Raw Results for Configuration 5

Wave Height (feet)											
Sea tate	S1	2	3	5	6	7	8	9	10	11	12
3.2	3.1436	3.3942	1.9858	1.8375	2.4534	1.7759	2.0704	2.2030	1.8333	2.1965	2.9288
4.2	7.4717	4.2402	3.1773	3.1259	4.0824	4.5850	4.6679	3.5799	3.2018	3.2677	6.7237
5.2	11.1610	7.0984	6.6591	7.4658	8.8415	5.9459	7.5092	8.1778	6.3661	7.0909	10.3414

Table 11 – Calibrated and Scaled Results Results for Configuration 5

Configuration 6

Stern-to-Bow Configuration – Head Seas

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
37	3 (10% less than MP)	0.2464	0.1548	0.0998	0.1285	0.1213	0.1623	0.1278	0.1822	0.1427	0.1495	0.1788
38	3 (Most probable)	0.2134	0.2634	0.1173	0.1437	0.1403	0.1603	0.1250	0.1659	0.1529	0.1523	0.2095
39	3 (!0% above MP)	0.2461	0.1975	0.1085	0.1583	0.1685	0.1630	0.1443	0.1955	0.1440	0.1570	0.2586
40	4 (10% less than MP)	0.4399	0.3060	0.2223	0.2616	0.2168	0.1666	0.2063	0.3282	0.2463	0.2560	0.3935
41	4 (Most probable)	0.4347	0.3743	0.2836	0.3229	0.2934	0.1748	0.2555	0.3505	0.2631	0.2817	0.4573
42	4 (!0% above MP)	0.4949	0.4565	0.3379	0.3425	0.3018	0.2201	0.2530	0.3738	0.2868	0.2999	0.5064
43	5 (Most probable)	0.8513	0.6470	0.4513	0.5426	0.4881	0.3698	0.4718	0.5878	0.3819	0.4873	0.8363
44	6 (Most probable)	1.3220	0.8979	1.0563	0.8510	0.8622	0.6929	0.8017	0.8371	0.9410	0.7643	1.2007
45	7 (Most probable)	0.4126	0.3325	0.3032	0.2873	0.2701	0.2271	0.2854	0.3100	0.2816	0.2616	0.4235

Table 12 – Raw Results for Configuration 6

	Wave Height (feet)										
Sea tate S	1	2	3	5	6	7	8	9	10	11	12
3 (10% less than MP)	3.2438	2.4376	2.1908	2.3617	1.9422	2.6514	2.2276	2.6670	2.3401	2.9800	2.3548
3 (Most probable)	2.8093	4.1767	2.3141	2.1381	2.3061	2.2591	2.0845	2.5277	2.2553	2.3679	3.4050
3 (!0% above MP)	3.2405	2.8536	2.0437	2.4514	2.0852	2.1410	2.0308	2.3681	2.0707	2.5168	5.1815
4 (10% less than MP)	5.7916	4.0418	3.2193	4.0475	3.2773	2.7002	3.1063	4.7026	3.7022	3.9146	5.1815
4 (Most probable)	5.7237	5.5419	4.5267	5.2258	4.6458	2.7553	4.0053	5.4691	4.0789	4.4793	6.0215
4 (!0% above MP)	6.5160	7.0916	6.0788	5.9469	4.8145	3.3805	4.3672	5.7260	4.5118	5.0096	6.6674
5 (Most probable)	11.2083	9.7569	7.5289	9.1484	7.7360	5.8606	7.2559	10.1794	6.5397	8.7052	11.0108
6 (Most probable)	17.4064	12.8384	15.7055	13.0159	12.7248	10.3891	10.8457	12.4893	13.6620	12.0353	15.8090
7 (Most probable)	5.4327	4.7537	4.5081	4.3937	3.9860	3.4049	3.8609	4.6246	4.0885	4.1192	5.5761

Table 13 – Calibrated and Scaled Results Results for Configuration 6

Configuration 7

Skin-to-Skin Configuration – Head Seas with Midships Level

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
46	3 (Most probable)	0.2790	0.2156	0.1399	0.1913	0.1245	0.1254	0.1408	0.1182	0.1279	0.1128	0.2115
47	4 (Most probable)	0.4933	0.5610	0.3552	0.3938	0.2570	0.1784	0.2998	0.1824	0.2160	0.2128	0.4295
48	5 (Most probable)	0.8249	0.9379	0.6694	0.7330	0.4377	0.3678	0.4343	0.2767	0.3877	0.3385	0.9595
49	6 (Most probable)	1.2863	1.2102	1.0017	1.0249	0.9065	0.7697	0.8475	0.7701	0.8734	0.7727	1.3456
50	7 (Most probable)	1.6779	1.7299	1.3258	1.5805	1.1954	1.0885	1.3342	1.1677	1.2247	1.1093	1.7892

Table 14 – Raw Results for Configuration 7

	Wave Height (feet)										
Szea State	1	2	3	5	6	7	8	9	10	11	12
3 (Most probable)	3.6733	3.4199	2.7587	2.8460	2.0461	1.7679	2.3477	1.8011	1.8861	1.7531	2.7842
4 (Most probable)	6.4947	8.3072	5.6692	6.3739	4.0698	2.8133	4.6995	2.8469	3.3487	3.3838	5.6555
5 (Most probable)	10.8606	14.1440	11.1670	12.3605	6.9363	5.8280	6.6793	4.7928	6.6382	6.0483	12.6332
6 (Most probable)	16.9356	17.3032	14.8949	15.6744	13.3795	11.5412	11.4655	11.4897	12.6811	12.1681	17.7171
7 (Most probable)	22.0918	24.7345	19.7141	24.1729	17.6423	16.3205	18.0488	17.4217	17.7810	17.4685	23.5576

Table 15 – Calibrated and Scaled Results Results for Configuration 7

Configuration 8

Skin-to-Skin Configuration at 30° to Head Seas with Midships Level

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
51	3 10%(ess than P) M	0.2084	0.0818	0.1203	0.1320	0.1387	0.1291	0.1358	0.1263	0.1343	0.1368	0.2061
52	3 (Most probable)	0.2085	0.1126	0.1304	0.1517	0.1612	0.1738	0.2326	0.1611	0.1561	0.1854	0.2118
53	3 !0%(above P) M	0.2357	0.2207	0.1038	0.1395	0.1284	0.1466	0.1410	0.1360	0.1572	0.1468	0.2354
54	4 10%(ess than P) M	0.4403	0.2939	0.2341	0.2720	0.2019	0.2038	0.2339	0.2251	0.2191	0.2377	0.4041
55	4 (Most probable)	0.4489	0.2903	0.2844	0.3435	0.2766	0.2125	0.3135	0.2837	0.2418	0.2813	0.5003
56	4 !0%(above P) M	0.5340	0.3766	0.3008	0.3282	0.3007	0.2089	0.3003	0.2805	0.2455	0.2955	0.4904
57	5 (Most probable)	0.7830	0.6469	0.4900	0.6043	0.4440	0.3132	0.4988	0.5210	0.4193	0.4027	0.8468
58	6 (Most probable)	1.1748	1.0844	0.9877	1.1841	0.8550	1.0389	0.9562	0.9555	0.7657	0.8957	1.0441
59	7 (Most probable)	1.7154	1.3240	1.4427	1.4087	1.0570	1.1879	1.1629	1.0685	1.0596	0.9814	1.8699

Table 16 – Raw Results for Configuration 8

	Wave Height (feet)										
Sea State	1	2	3	5	6	7	8	9	10	11	12
3 (10% less than MP)	2.7435	1.2881	2.6407	2.4266	2.2212	2.1093	2.3676	1.8483	2.2023	2.7267	2.7137
3 (Most probable)	2.7446	1.7850	2.5719	2.2569	2.6492	2.4490	3.8787	2.4546	2.3031	2.8817	3.0993
3 (!0% above MP)	3.1028	3.1883	1.9552	2.1595	1.5889	1.9257	1.9847	1.6481	2.2611	2.3530	5.3213
4 (10% less than MP)	5.7975	3.8823	3.3896	4.2094	3.0520	3.3021	3.5227	3.2251	3.2932	3.6348	5.3213
4 (Most probable)	5.9112	4.2985	4.5384	5.5586	4.3797	3.3511	4.9148	4.4266	3.7490	4.4725	6.5875
4 (!0% above MP)	7.0307	5.8502	5.4108	5.6988	4.7969	3.2083	5.1828	4.2967	3.8624	4.9363	6.4571
5 (Most probable)	10.3097	9.7558	8.1751	10.1888	7.0373	4.9626	7.6720	9.0227	7.1796	7.1944	11.1500
6 (Most probable)	15.4684	15.5054	14.6864	18.1100	12.6187	15.5776	12.9353	14.2557	11.1168	14.1037	13.7478
7 (Most probable)	22.5862	18.9301	21.4514	21.5451	15.5998	17.8115	15.7309	15.9429	15.3846	15.4540	24.6207

Table 17 – Calibrated and Scaled Results Results for Configuration 8

Configuration 9

Skin-to-Skin Configuration at 60° to Head Seas with Midships Level

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
60	3 (10% less than MP)	0.2467	0.1353	0.0896	0.1203	0.1341	0.1699	0.1823	0.1249	0.0926	0.1048	0.2017
61	3 (Most probable)	0.1276	0.0423	0.0655	0.1539	0.1223	0.1275	0.1512	0.0996	0.0707	0.1151	0.1491
62	3 (!0% above MP)	0.2575	0.1125	0.1051	0.1577	0.1318	0.1973	0.2413	0.1237	0.0850	0.1074	0.2427
63	4 (10% less than MP)	0.4026	0.2650	0.2511	0.2525	0.1902	0.1553	0.1778	0.1909	0.1368	0.1899	0.4402
64	4 (Most probable)	0.4044	0.3263	0.3164	0.3146	0.2605	0.1967	0.2741	0.2071	0.1489	0.1630	0.4425
65	4 (!0% above MP)	0.1361	0.0848	0.0886	0.0880	0.0689	0.0597	0.0729	0.0596	0.0464	0.0432	0.1326
66	5 (Most probable)	0.7605	0.5370	0.5563	0.5654	0.5263	0.3985	0.4394	0.3438	0.2308	0.3035	0.7922
67	6 (Most probable)	1.2884	1.1400	1.0884	0.9483	0.9849	0.8872	0.9133	0.8706	0.8075	0.8573	1.2162
68	7 (Most probable)	1.7888	1.3298	1.3993	1.3726	1.2836	1.1696	1.2608	1.1877	1.1388	1.1326	1.5252

Table 18 – Raw Results for Configuration 9

	Wave Height (feet)										
Sea State	1	2	3	5	6	7	8	9	10	11	12
3 (10% less than MP)	3.2481	2.1305	1.9659	2.2113	2.1480	2.7753	3.1775	1.8281	1.5195	2.0884	2.6560
3 (Most probable)	1.6796	0.6710	1.2909	2.2897	2.0105	1.7968	2.5208	1.5173	1.0432	1.7889	3.1958
3 (!0% above MP)	3.3909	1.6245	1.9800	2.4422	1.6316	2.5913	3.3958	1.4985	1.2228	1.7213	5.7960
4 (10% less than MP)	5.3007	3.4998	3.6369	3.9067	2.8754	2.5157	2.6770	2.7361	2.0568	2.9042	5.7960
4 (Most probable)	5.3246	4.8310	5.0495	5.0919	4.1259	3.1012	4.2971	3.2312	2.3085	2.5918	5.8256
4 (!0% above MP)	1.7914	1.3166	1.5942	1.5286	1.0998	0.9170	1.2589	0.9132	0.7296	0.7222	1.7460
5 (Most probable)	10.0129	8.0978	9.2807	9.5340	8.3405	6.3153	6.7589	5.9544	3.9519	5.4224	10.4305
6 (Most probable)	16.9645	16.2991	16.1829	14.5031	14.5354	13.3021	12.3556	12.9888	11.7246	13.4989	16.0138
7 (Most probable)	23.5519	19.0134	20.8057	20.9922	18.9445	17.5370	17.0561	17.7200	16.5348	17.8351	20.0816

Table 19 – Calibrated and Scaled Results Results for Configuration 9

Configuration 10

Med-Moor Configuration with MV Blue Marlin (Confused Seas)

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
70	3 (Most probable)	0.1610	0.1758	0.1075	0.1538	0.1623	0.1375	0.1681	0.1374	0.1521	0.1601	0.2007
71	4 (Most probable)	0.4593	0.3501	0.3706	0.3351	0.3315	0.2789	0.3029	0.2396	0.2692	0.3368	0.4701
72	5 (Most probable)	0.7601	0.5229	0.5500	0.4450	0.4821	0.3310	0.4504	0.4066	0.4308	0.3513	0.8839

Table 20 – Raw Results for Configuration 10

Wave Height (feet)											
Sea State	1	2	3	5	6	7	8	9	10	11	12
3 (Most probable)	2.1194	2.7888	2.1212	2.2884	2.6675	1.9375	2.8032	2.0943	2.2432	2.4894	2.6427
4 (Most probable)	6.0469	5.1844	5.9150	5.4225	5.2499	4.3967	4.7474	3.7382	4.1731	5.3549	6.1902
5 (Most probable)	10.0083	7.8855	9.1750	7.5040	7.6407	5.2451	6.9275	7.0419	7.3770	6.2764	11.6375

Table 21 – Calibrated and Scaled Results Results for Configuration 10

Configuration 11

Skin-to-Skin Configuration – Beam Seas with Midships Level (Confused Seas)

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
73	3 (Most probable)	0.1783	0.1662	0.0856	0.1202	0.1411	0.1655	0.1371	0.1266	0.1166	0.0949	0.1810
74	4 (Most probable)	0.4521	0.2545	0.1897	0.1890	0.2240	0.1510	0.2188	0.0362	0.1978	0.2153	0.6035
78	5 (Most probable)	0.6156	0.3303	0.2565	0.2773	0.2522	0.1933	0.2725	0.2455	0.3285	0.2187	0.5252

Table 22 – Raw Results for Configuration 11

Wave Height (feet)											
Sea tate S	1	2	3	5	6	7	8	9	10	11	12
3 (Most probable)	2.3476	2.6354	1.6879	1.7888	2.3190	2.3334	2.2854	1.9297	1.7192	1.4755	2.3831
4 (Most probable)	5.9525	3.7687	3.0267	3.0584	3.5477	2.3807	3.4296	0.5654	3.0662	3.4239	7.9456
5 (Most probable)	8.1051	4.9817	4.2790	4.6759	3.9964	3.0636	4.1909	4.2516	5.6249	3.9076	6.9151

Table 23 – Calibrated and Scaled Results Results for Configuration 11

Configuration 12

Skin-to-Skin Configuration – Beam Seas with Midships Level (Run No. 2)

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
77	3 (Most probable)	0.2548	0.0819	0.0912	0.1336	0.1334	0.1125	0.1210	0.0386	0.1411	0.1193	0.2310
76	4 (Most probable)	0.4536	0.3290	0.2242	0.2647	0.3047	0.1997	0.2601	0.0061	0.2263	0.2145	0.4998
75	5 (Most probable)	0.6978	0.3466	0.2823	0.3055	0.3741	0.2957	0.3648	0.0530	0.3545	0.3591	0.6743

Table 24 – Raw Results for Configuration 12

Wave Height (feet)											
Sea State	1	2	3	5	6	7	8	9	10	11	12
3 (Most probable)	3.3554	1.2984	1.7996	1.9871	2.1927	1.5853	2.0182	0.0000	2.0813	1.8545	3.0421
4 (Most probable)	5.9721	4.8716	3.5785	4.2840	4.8248	3.1483	4.0765	0.0000	3.5080	3.4107	6.5808
5 (Most probable)	9.1872	5.2272	4.7095	5.1513	5.9287	4.6865	5.6110	0.0000	6.0699	6.4159	8.8778

Table 25 – Calibrated and Scaled Results Results for Configuration 12

Configuration 13

Skin-to-Skin Configuration – Beam Seas with Reduced Separation

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
79	3 (Most probable)	0.2259	0.1405	0.0956	0.1330	0.1545	0.1470	0.1341	0.1395	0.1291	0.1235	0.2222
80	4 (Most probable)	0.4224	0.2813	0.2639	0.2470	0.2990	0.2589	0.2710	0.2057	0.2055	0.2592	0.4479
81	5 (Most probable)	0.8014	0.4483	0.5006	0.5013	0.6743	0.5687	0.6262	0.4453	0.4126	0.4391	0.9020

Table 26 – Raw Results for Configuration 13

Wave Height (feet)											
Sea tate S	1	2	3	5	6	7	8	9	10	11	12
3 (Most probable)	2.9743	2.2285	1.8858	1.9781	2.5398	2.0721	2.2358	2.1262	1.9037	1.9195	2.9251
4 (Most probable)	5.5619	4.1650	4.2113	3.9970	4.7353	4.0814	4.2476	3.2102	3.1860	4.1211	5.8975
5 (Most probable)	10.5522	6.7608	8.3512	8.4531	10.6867	9.0123	9.6305	7.7123	7.0657	7.8452	11.8757

Table 27 – Calibrated and Scaled Results Results for Configuration

Configuration 14

Med-Moor Configuration with MV Blue Marlin (Varying Probe Position)

Run Number	Sea State	Wave Height (feet)										
		1	2	3	5	6	7	8	9	10	11	12
82	4 (Most Probable)	0.4914	0.3132	0.2789	0.2837	0.3553	0.2064	0.2686	0.2878	0.2890	0.2875	0.4443
83	4 (Most Probable)	0.5090	0.2882	0.3117	0.3248	0.3109	0.2197	0.2807	0.2740	0.2996	0.2919	0.4408
84	4 (Most Probable)	0.4811	0.3517	0.3872	0.3629	0.2804	0.2511	0.2599	0.2053	0.3036	0.2397	0.4380
85	4 (Most Probable)	0.4763	0.4412	0.4235	0.4045	0.3188	0.2848	0.3146	0.2653	0.3101	0.2680	0.4631
86	4 (Most Probable)	0.4693	0.4039	0.3946	0.3796	0.3826	0.2162	0.3343	0.2791	0.2879	0.3116	0.4255
87	4 (Most Probable)	0.5121	0.2742	0.2713	0.2383	0.3787	0.2220	0.2997	0.2963	0.2490	0.2985	0.4516
88	4 (Most Probable)	0.4245	0.3289	0.2712	0.2327	0.3531	0.2470	0.3269	0.2558	0.2428	0.3146	0.4373
89	4 (Most Probable)	0.4751	0.3837	0.3491	0.3135	0.3401	0.2325	0.2924	0.2287	0.2210	0.2867	0.4447
90	4 (Most Probable)	0.4732	0.3415	0.3968	0.3816	0.3064	0.2268	0.3092	0.2528	0.2922	0.2825	0.4571
91	4 (Most Probable)	0.4815	0.3610	0.3580	0.3656	0.3450	0.2404	0.3048	0.2696	0.2806	0.3034	0.4293
92	4 (Most Probable)	0.4923	0.3611	0.3906	0.3312	0.4097	0.2161	0.3422	0.2395	0.2357	0.2850	0.4503
93	4 (Most Probable)	0.4769	0.3474	0.2929	0.2277	0.3372	0.2411	0.2961	0.2402	0.2577	0.2814	0.4366

Table 28 – Raw Results for Configuration 14

Wave Height (feet)											
Sea tate S	1	2	3	5	6	7	8	9	10	11	12
4 (Most Probable)	6.4707	4.6378	4.4514	4.5909	5.6264	3.2544	4.2097	4.4906	4.4799	4.5714	5.8503
4 (Most Probable)	6.7018	4.2681	4.9744	5.2562	4.9237	3.4632	4.3994	4.2754	4.6452	4.6416	5.8036
4 (Most Probable)	6.3344	5.2080	6.1788	5.8727	4.4400	3.9587	4.0737	3.2039	4.7065	3.8105	5.7667
4 (Most Probable)	6.2714	6.5329	6.7591	6.5459	5.0484	4.4905	4.9316	4.1405	4.8070	4.2614	6.0972
4 (Most Probable)	6.1794	5.9808	6.2981	6.1432	6.0595	3.4083	5.2400	4.3547	4.4632	4.9543	5.6025
4 (Most Probable)	6.7430	4.0608	4.3293	3.8572	5.9964	3.5001	4.6971	4.6244	3.8610	4.7468	5.9467
4 (Most Probable)	5.5890	4.8701	4.3287	3.7654	5.5909	3.8937	5.1235	3.9915	3.7634	5.0022	5.7575
4 (Most Probable)	6.2551	5.6812	5.5714	5.0742	5.3855	3.6658	4.5829	3.5682	3.4256	4.5589	5.8556
4 (Most Probable)	6.2298	5.0575	6.3322	6.1761	4.8519	3.5762	4.8461	3.9445	4.5294	4.4918	6.0187
4 (Most Probable)	6.3400	5.3452	5.7132	5.9174	5.4625	3.7897	4.7779	4.2065	4.3503	4.8240	5.6529
4 (Most Probable)	6.4821	5.3471	6.2336	5.3600	6.4883	3.4077	5.3645	3.7366	3.6538	4.5313	5.9285
4 (Most Probable)	6.2796	5.1440	4.6748	3.6857	5.3398	3.8020	4.6409	3.7486	3.9948	4.4750	5.7492

Table 29 – Calibrated and Scaled Results Results for Configuration 14

Appendix C – Results Graphs

The graphs in Figure 24 to Figure 36 show the leeward wave probes over a series of sea states. The graphs are arranged to show their relative position to each other as indicated in Figure 23. A 45° line is included on each graph as an indication of where the windward and leeward wave heights are equal, and hence where there is no reduction.

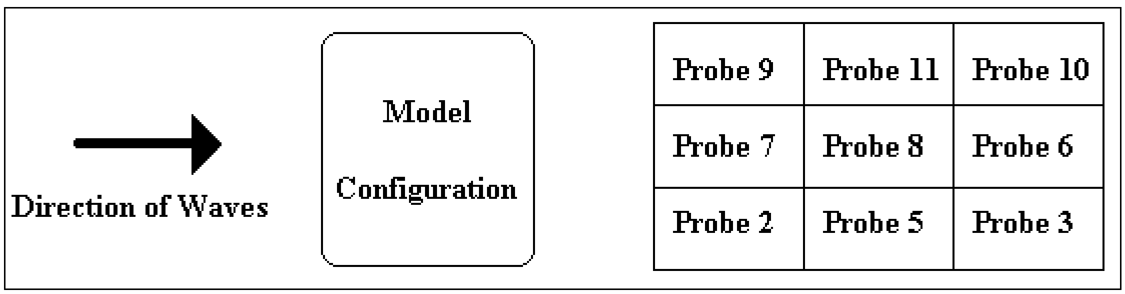


Figure 23 - Relative Position of Probes

Figure 37 shows a graph for configuration 14 when the positions of the probes were varied to give a total of 108 probe positions.

Configuration 1

Med-Moor Configuration with Tai An Kou

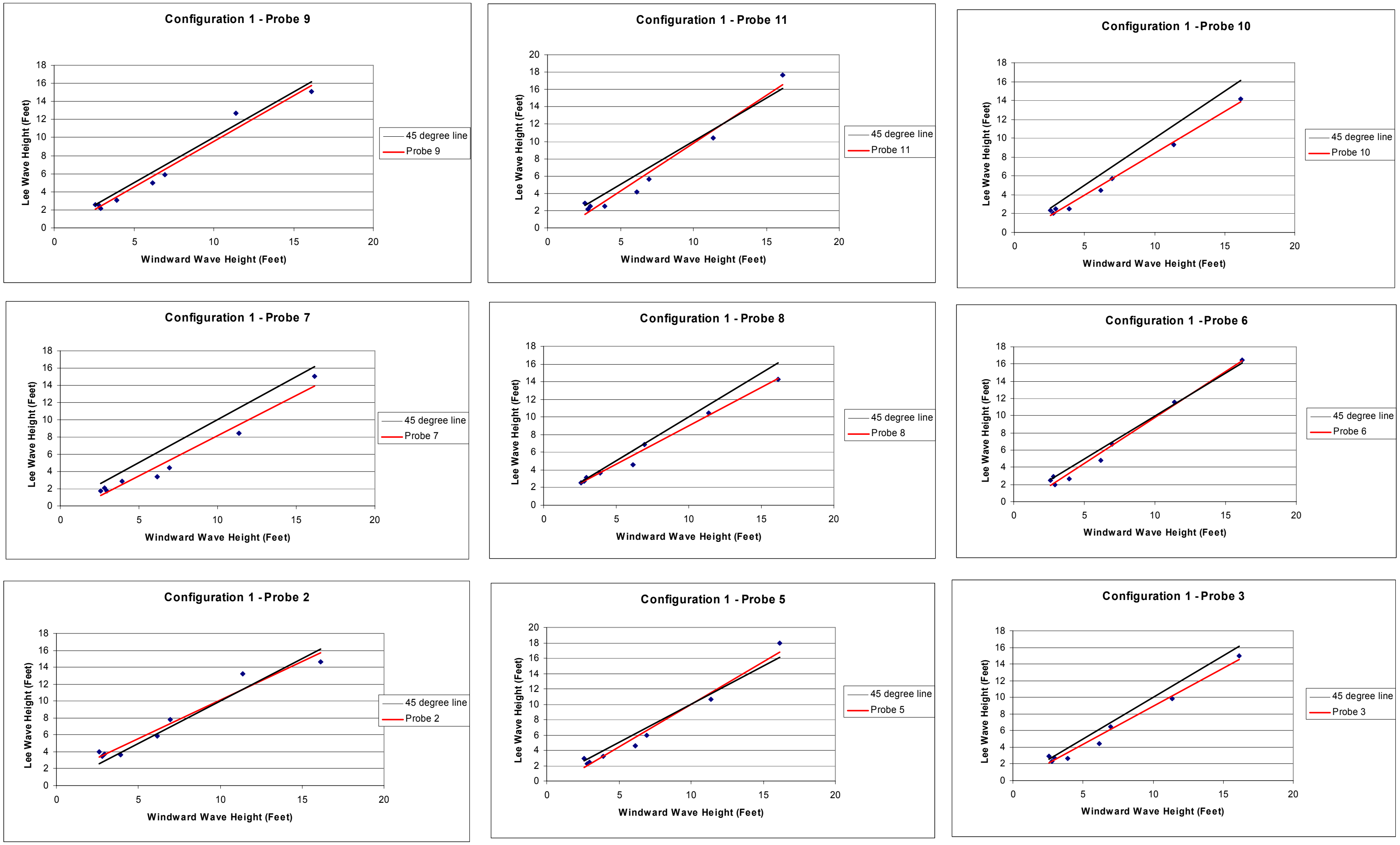


Figure 24 - Results Obtained from Configuration 1

Configuration 2

Med-Moor Configuration with MV Blue Marlin

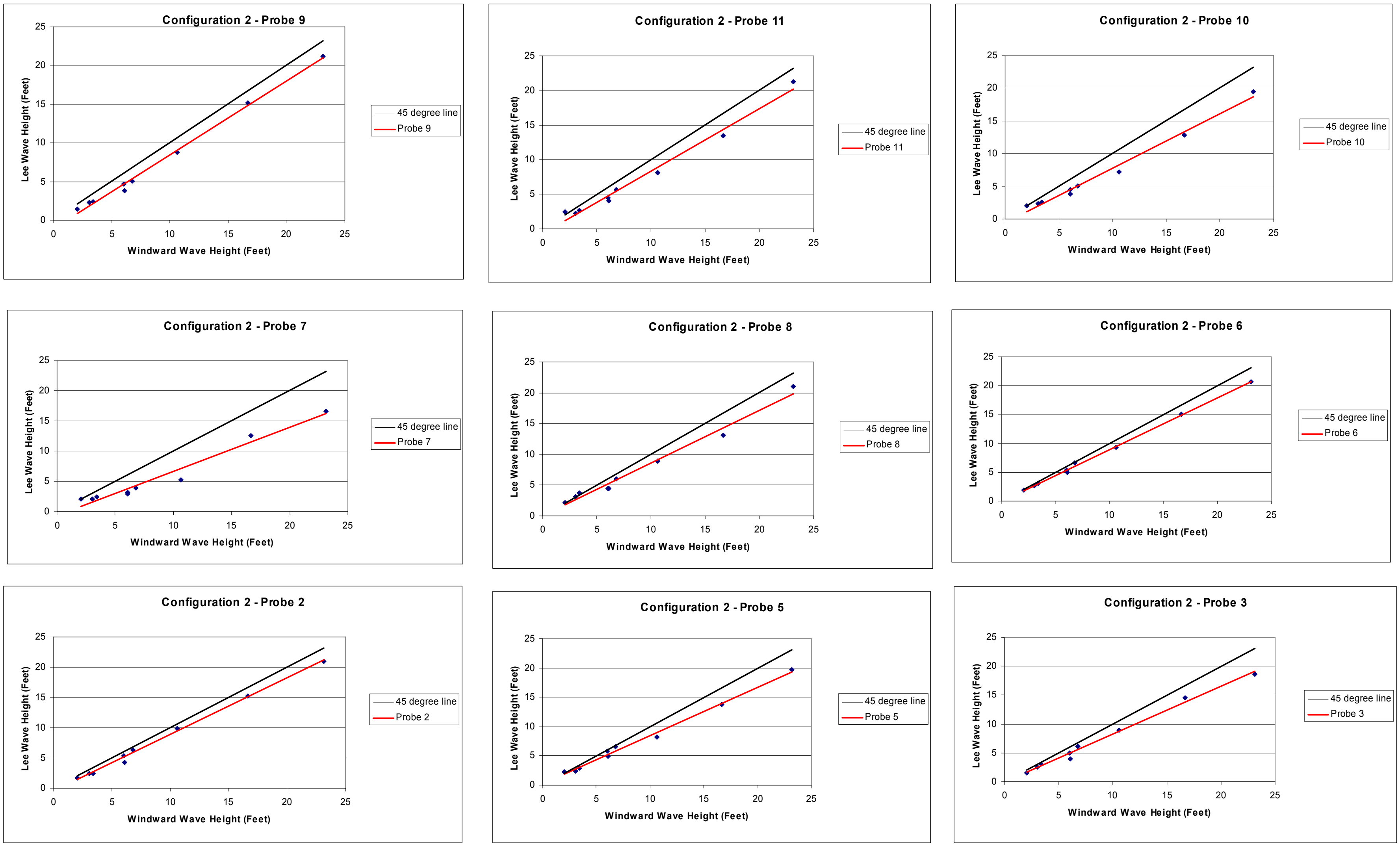


Figure 25 - Results Obtained from Configuration 2

Configuration 3

Skin-to-Skin Configuration – Beam Seas with Sterns Level

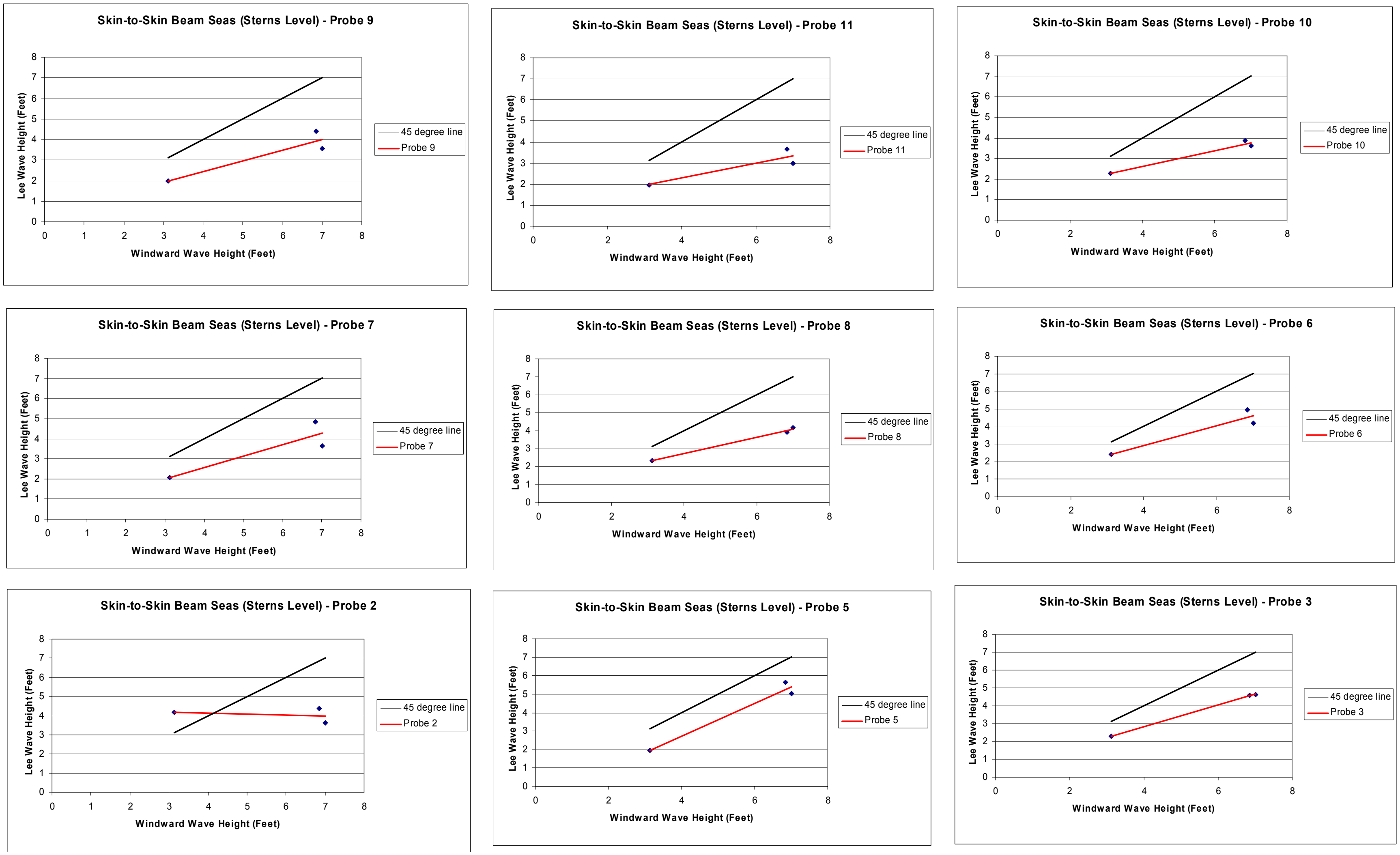


Figure 26 - Results Obtained from Configuration 3

Configuration 4

Skin-to-Skin Configuration – Beam Seas with Midships Level

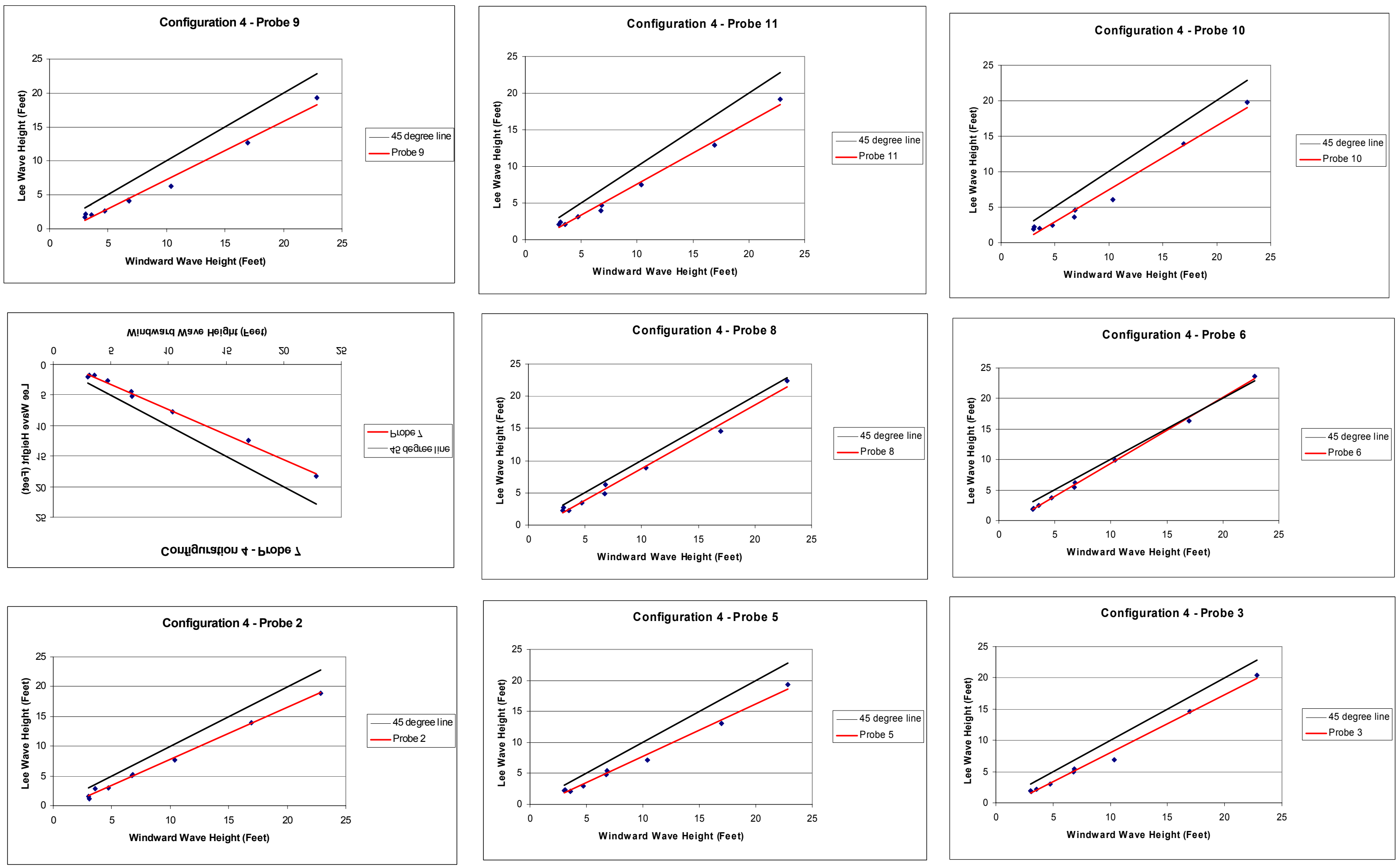


Figure 27 - Results Obtained from Configuration 4

Configuration 5

Skin-to-Skin Configuration – Beam Seas with Bows Level

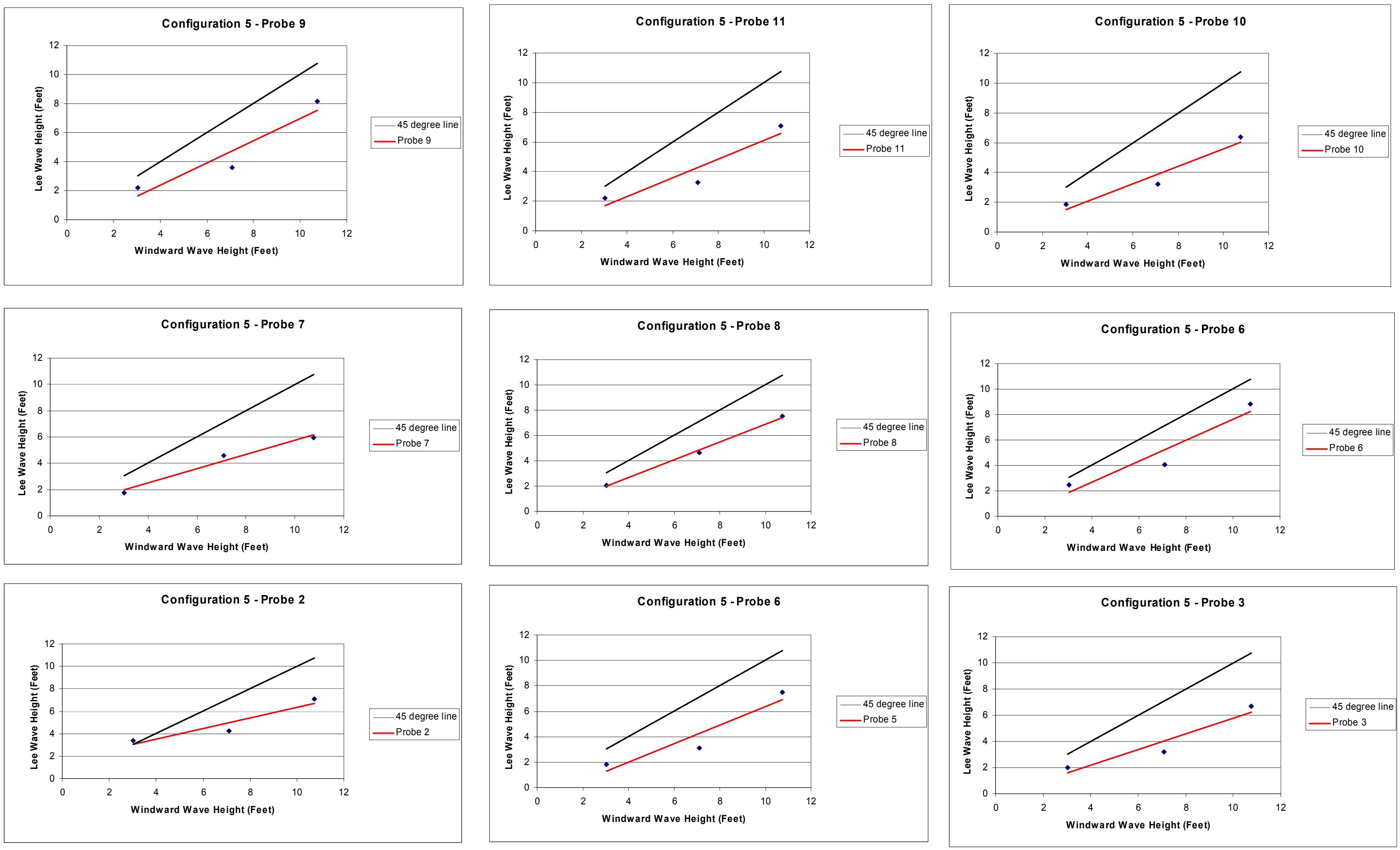


Figure 28 - Results Obtained from Configuration 5

Configuration 6

Stern-to-Bow Configuration in Head Seas

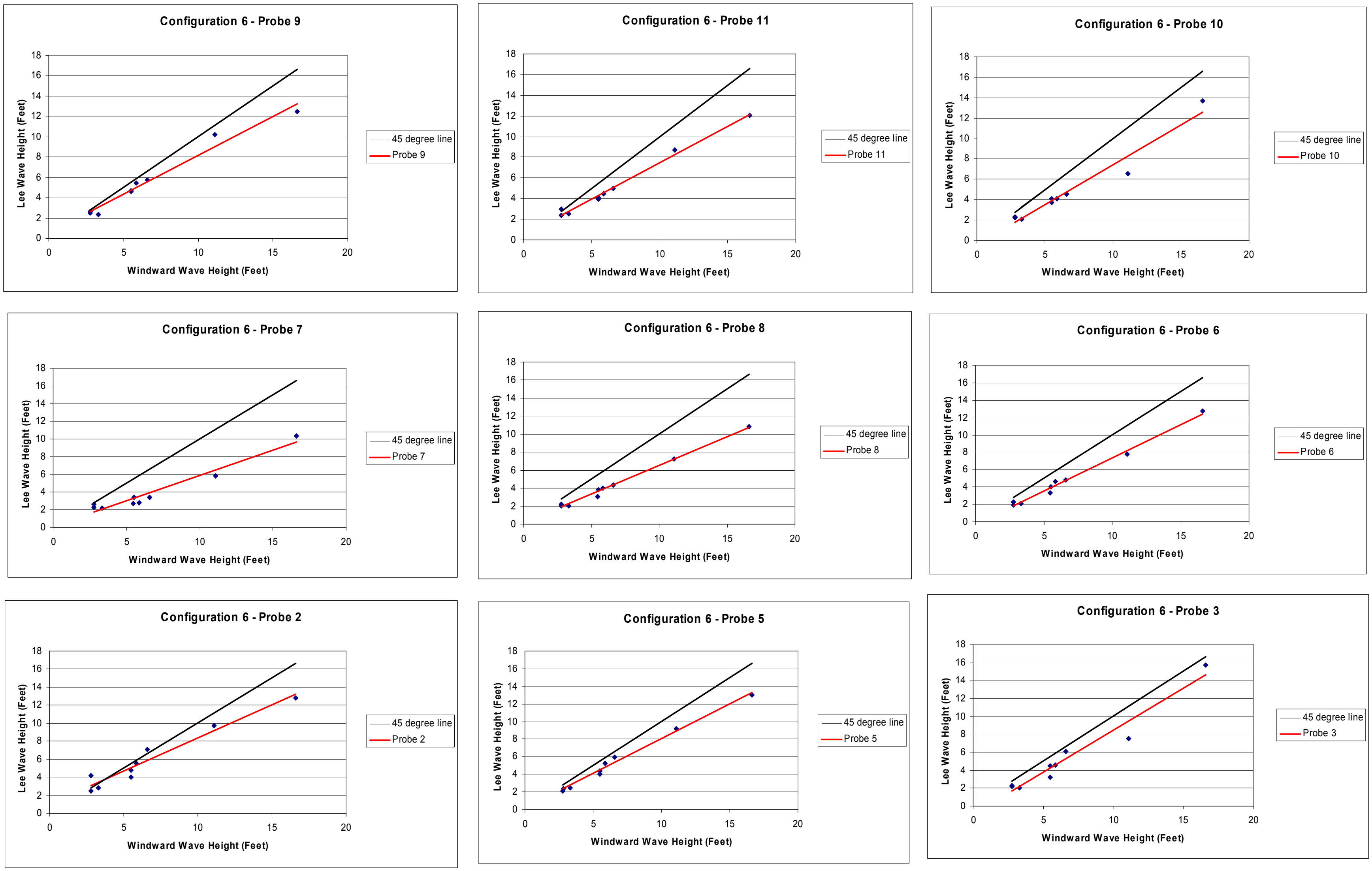


Figure 29 - Results Obtained from Configuration 6

Configuration 7

Skin-to-Skin Configuration – Head Seas with Midships Level

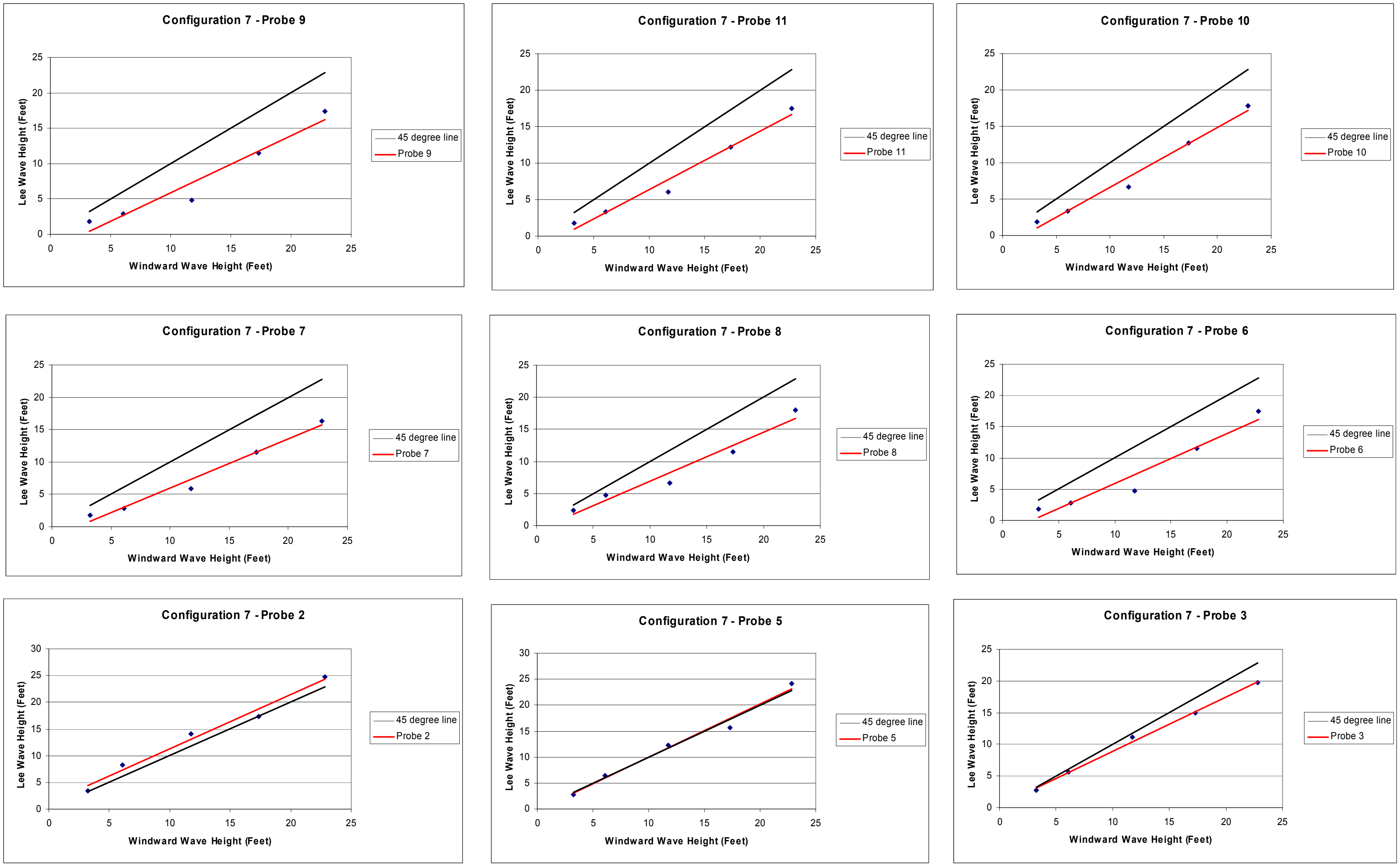


Figure 30 - Results Obtained from Configuration 7

Configuration 8

Skin-to-Skin Configuration at 30° to Head Seas with Midships Level

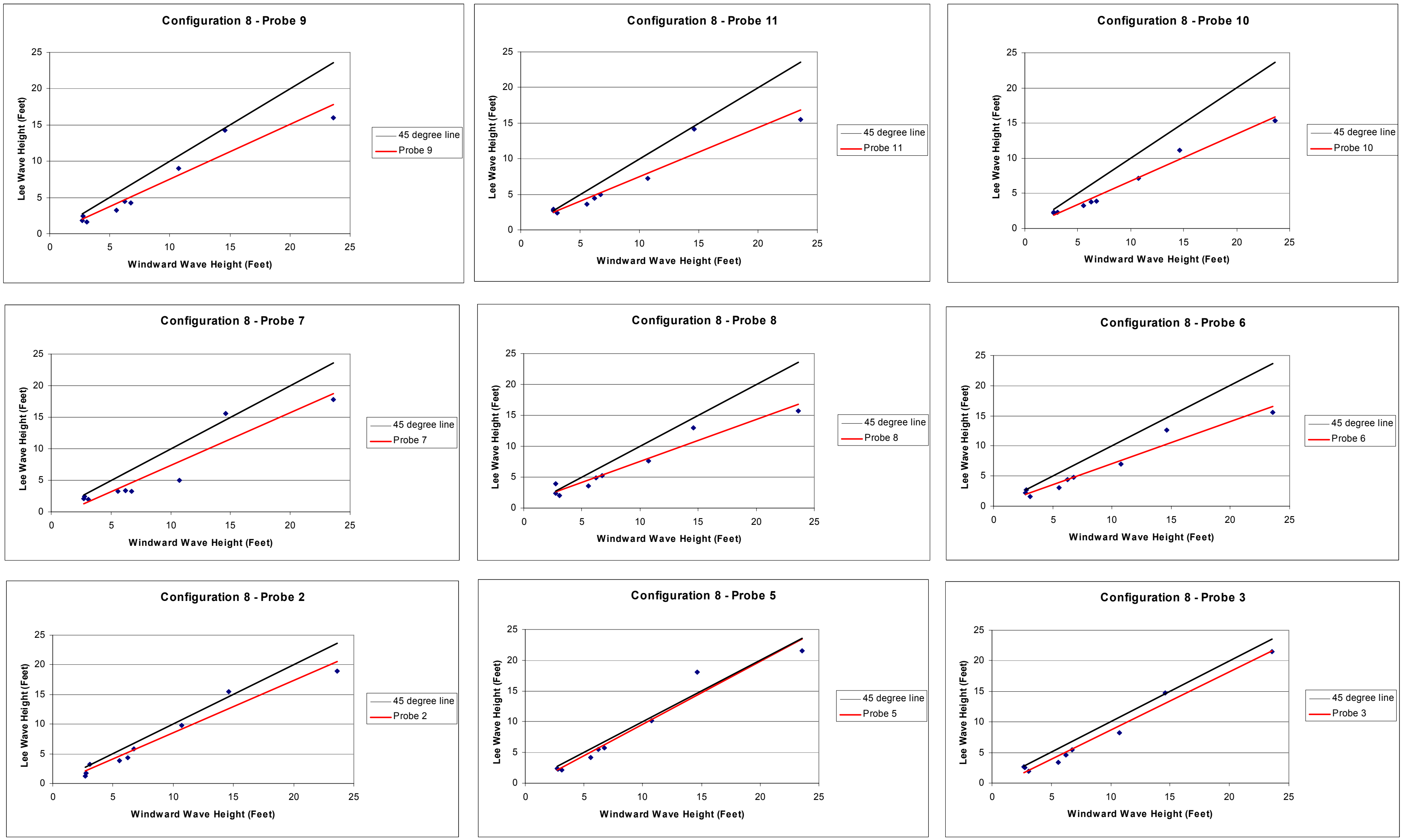


Figure 31 - Results Obtained from Configuration 8

Configuration 9

Skin-to-Skin Configuration at 60° to Head Seas with Midships Level

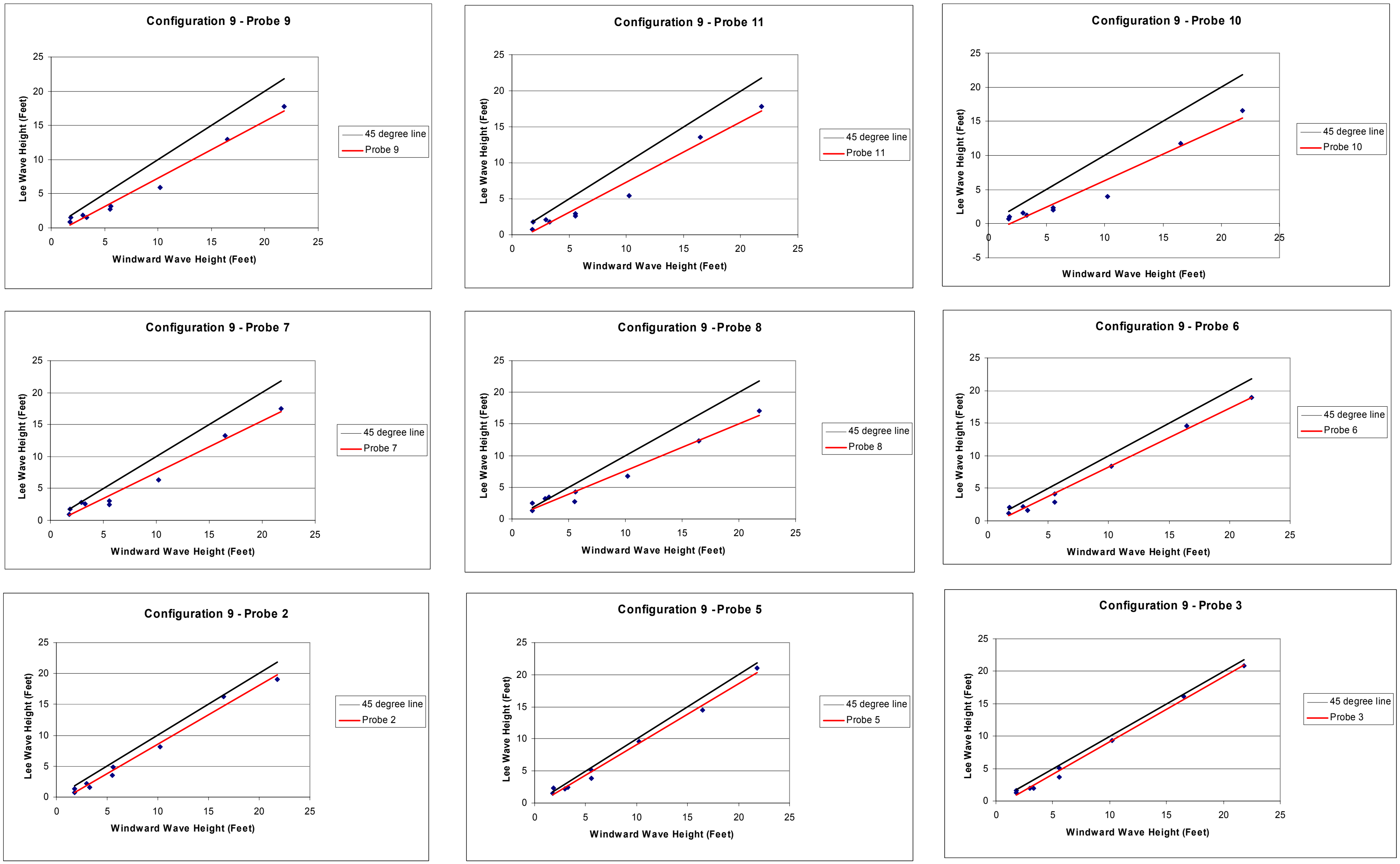


Figure 32 - Results Obtained from Configuration 9

Configuration 10

Med-Moor Configuration with MV Blue Marlin (Confused Seas)

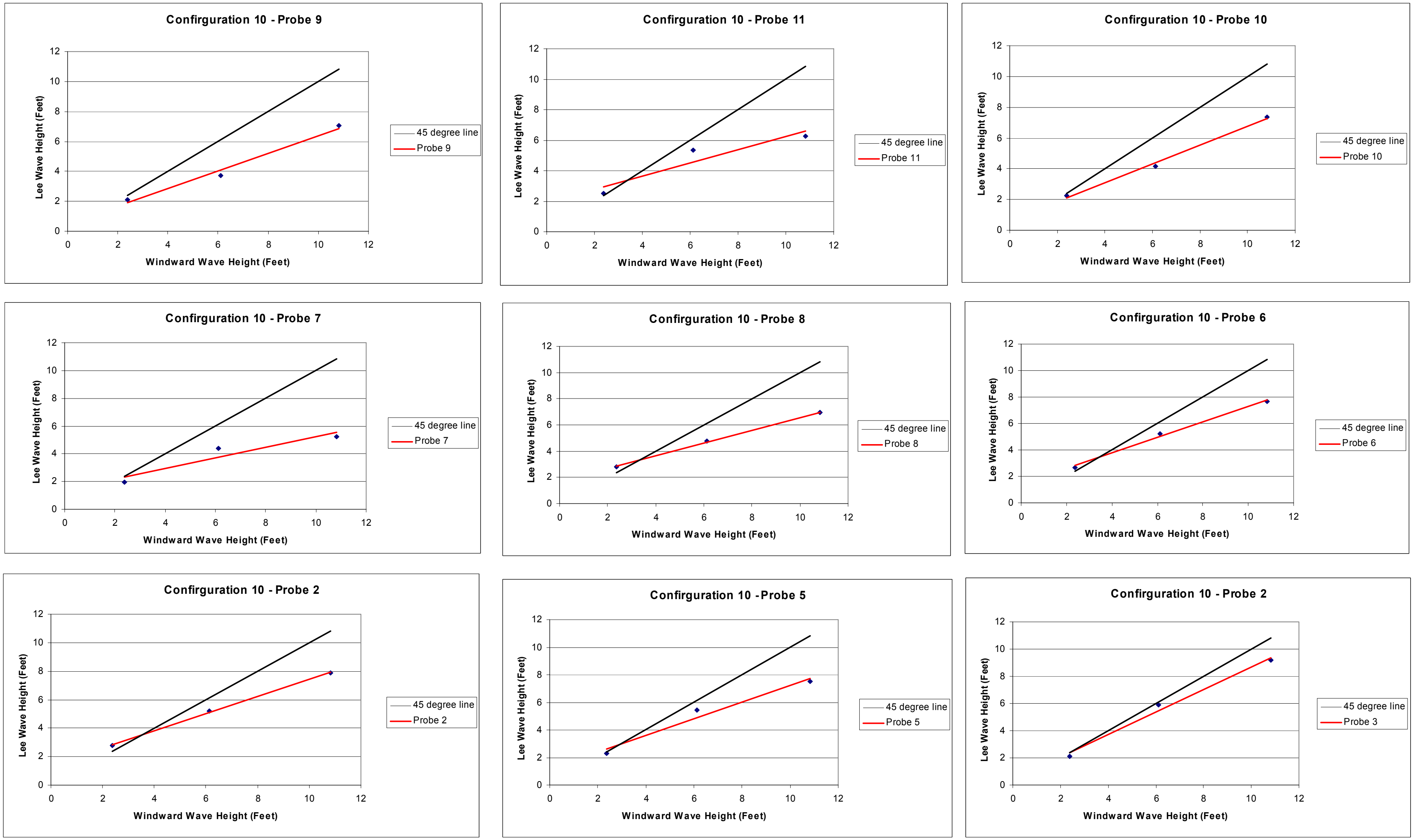


Figure 33 - Results Obtained from Configuration 10

Configuration 11

Skin-to-Skin Configuration – Beam Seas with Midships Level (Confused Seas)

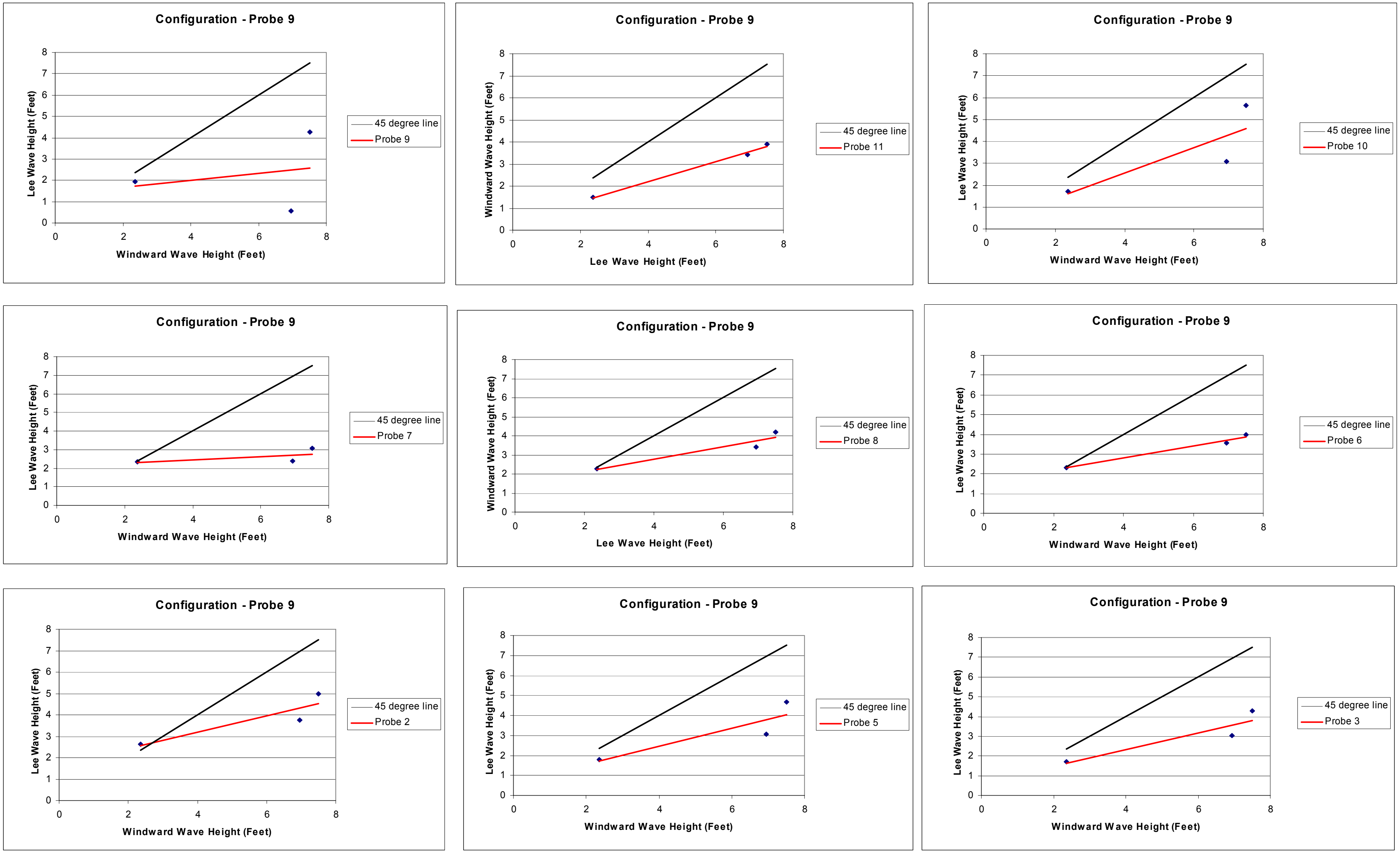


Figure 34 - Results Obtained from Configuration 11

Configuration 12

Skin-to-Skin Configuration – Beam Seas with Midships Level (Run No. 2)

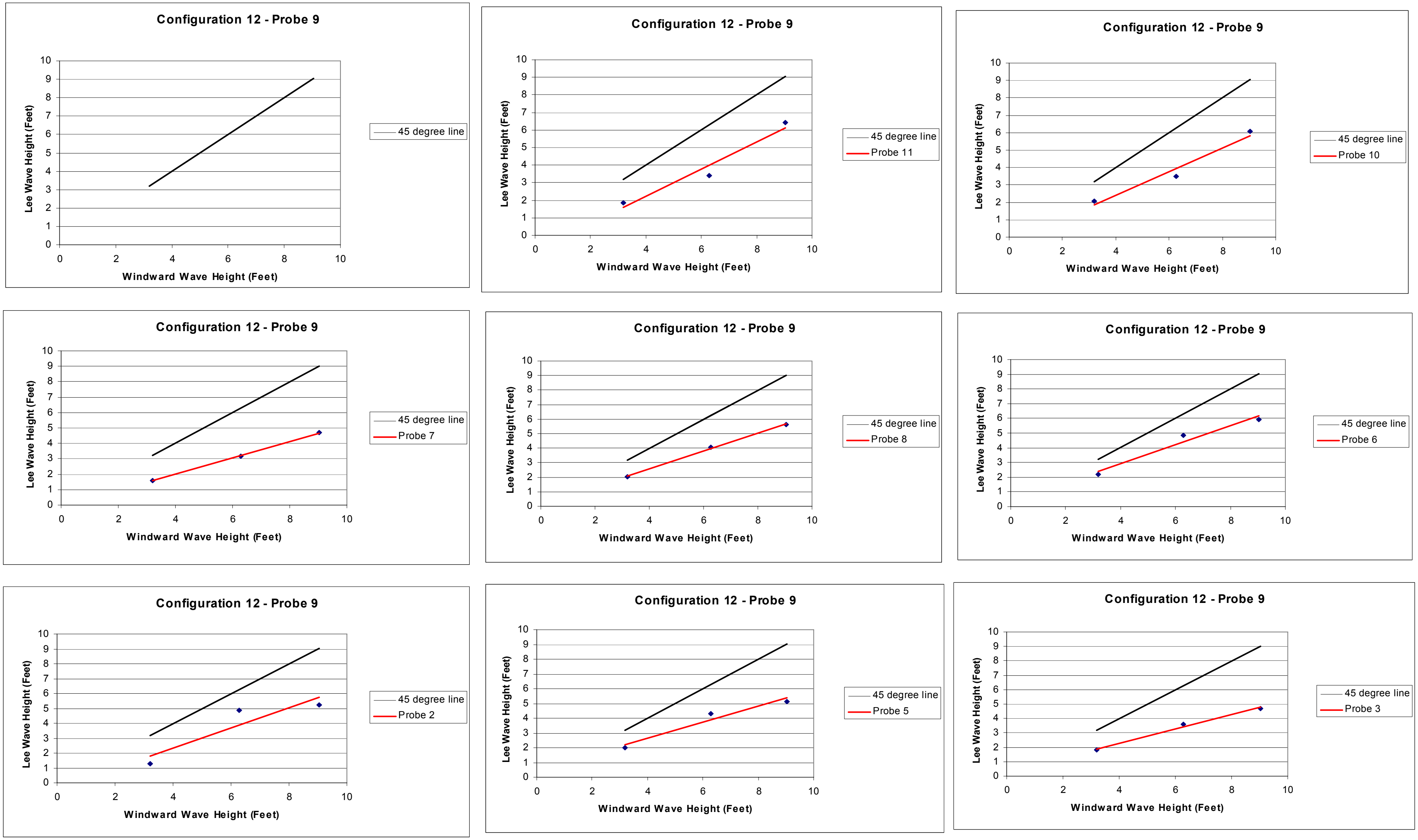


Figure 35 - Results Obtained from Configuration 12

Configuration 13

Skin-to-Skin Configuration – Beam Seas with Reduced Separation

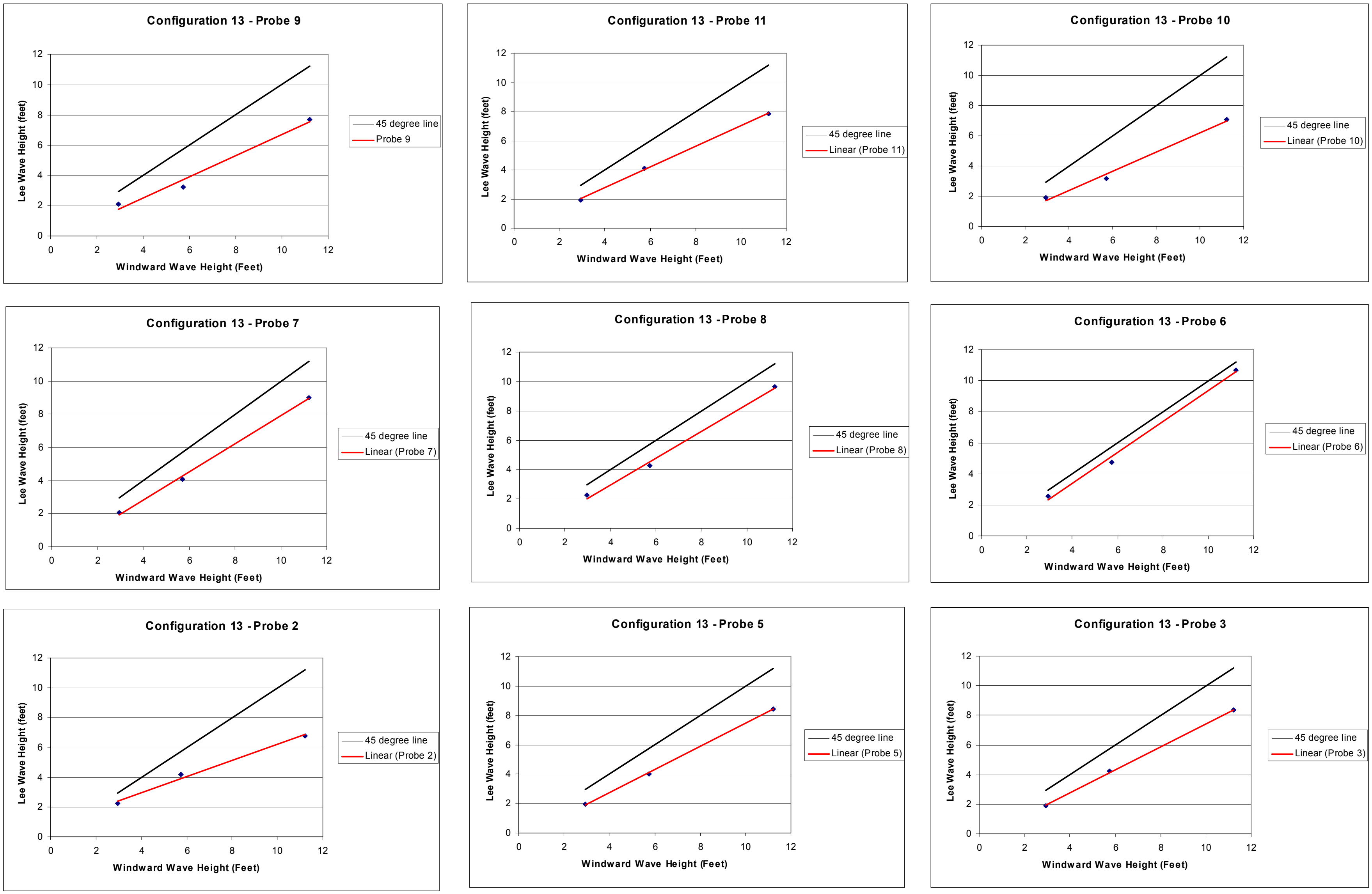


Figure 36 - Results Obtained from Configuration 13

Configuration 14

Med-Moor Configuration with MV Blue Marlin (Varying Probe Position)

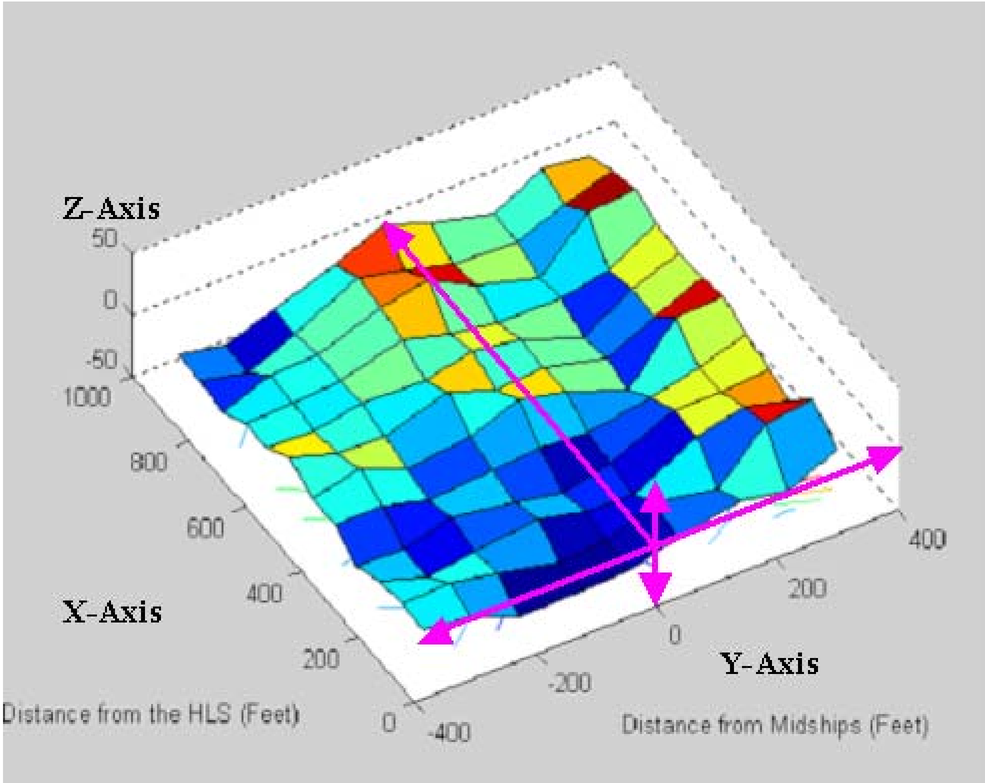


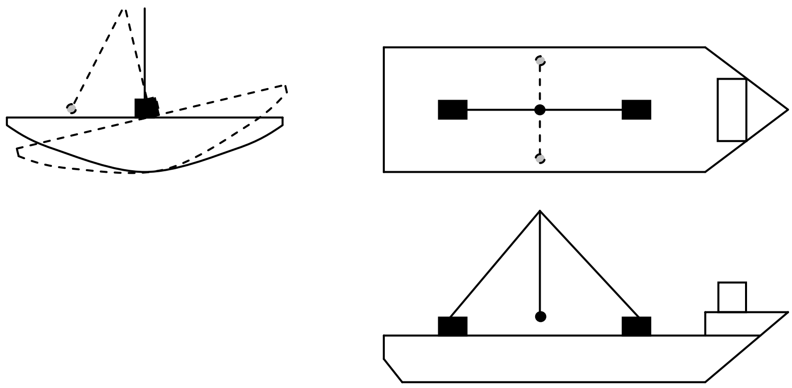
Figure 37 - Med-Moor Configuration (Varying Probe Position)

Figure 37 shows a 3D graph of the reduction in significant wave height for the med-moor configuration with the Blue Marlin. The Y-axis indicates the distance from the centre of midships of the HLS, the X-axis indicates the longitudinal distance from the HLS. The Z-axis indicates the percentage change in significant wave height.

The dark patches of blue show the greatest reduction in significant wave height, close to the centre of the HLS as expected, and the red patches illustrate the smallest reduction in wave height.

Appendix D – Inclining Experiment

The inclining experiment consisted of a pendulum system placed on the deck of the model. Starting from the center of the model a weight was moved so as to cause a heel angle, and the distance that the pendulum moved from its origin was recorded. The same weight was then moved further out, so as to increase the heel angle, and again the distance the pendulum had moved from the center was recorded. The weight was then returned to its original position, location recorded, and then the same test was completed in the opposite direction.



The purpose of the experiment is to calculate the GM of the model. This then allows for an approximation to be made on the ballast weight required to simulate the characteristics of the full scale ship. The chart below shows the calculations made, with the required ballast weight for the model calculated to be 15.420 kg.

Full Scale				
Weight Inclined (tons)		Vcg Inclined (m)		Vmt Ship
65339.3900	x	11.5019	=	751530.1593
Ballast Weight (tons)		Vcg Ballast (m)		Vmt Ballast
61302.6100	x	3.6208	=	221966.8947
Sum Weigh (tons)		Vcg System		Sum Vmt
126642.0000	x	7.6870	=	973497.0540
KMt (m)		GMt (m)		Vcg Inclined (m)
46.5960	-	35.0941	=	11.5019
VCB (m)		BMT (m)		KMt (m)
4.2300	+	42.3660	=	46.5960

158th Scale				
Weight Inclined (kg)		Vcg Inclined (m)		Vmt Ship
16.5655	x	0.0728	=	1.2059
Ballast Weight (kg)		Vcg Ballast (m)		Vmt Ballast
15.5420	x	0.0229	=	0.3562
Sum Weight (kg)		Vcg System (m)		Sum Vmt
32.1075	x	0.0487	=	1.5621
KMt (m)		GMt (m)		Vcg Inclined (m)
0.2949	-	0.2221	=	0.0728
VCB (m)		BMT (m)		KMt (m)
0.0268	+	0.2681	=	0.2949